SEASONAL NITROUS OXIDE EMISSION FROM DIFFERENT LAND USE IN TROPICAL RIPARIAN ECOSYSTEM :
A CASE STUDY IN NAN PROVINCE, NORTHERN THAILAND

Mr. Boonlue Kachenchart

A Dissertation Submitted in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy Program in Biological Sciences
Faculty of Science
Chulalongkorn University
Academic Year 2011

การปลดปล่อยไนตรัสออกไซด์ตามฤดูกาลจากการใช้ที่ดินแบบต่างๆ
ในระบบนิเวศริมน้ำเขตร้อน
กรณีศึกษา จังหวัดน่าน ภาคเหนือของประเทศไทย

นายบุญลือ คะเชนทร์ชาติ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
สาขาวิชาวิทยาศาสตรชีวภาพ
คณะวิทยาศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2554

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Thesis Title	SEASONAL NITROUS OXIDE EMISSION FROM DIFFERENT LAND USE IN TROPICAL RIPARIAN ECOSYSTEM: A CASE STUDY IN NAN PROVINCE, NORTHERN THAILAND
By	Mr. Boonlue Kachenchart
Field of Study	Biological Sciences
Thesis Advisor	Associate Professor Nantana Gajaseni, Ph.D.
Thesis Co-advisors	Professor Davey Jones, Ph.D. Atsamon Limsakul, Ph.D.

Accepted by the Faculty of Science, Chulalongkorn University in Partial Fulfillment of the Requirements for the Doctoral Degree

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บุญลือ คะเชนทร์ชาติ : การปลดปล่อยไนตรัสออกไซด์ตามฤดูกาลจากการใช้ที่ดินแบบต่างๆ ในระบบนิเวศริมน้ำเขตร้อน กรณีศึกษา จังหวัดน่าน ภาคเหนือของประเทศไทย (SEASONAL NITROUS OXIDE EMISSION FROM DIFFERENT LAND USE IN TROPICAL RIPARIAN ECOSYSTEM : A CASE STUDY IN NAN PROVINCE, NORTHERN THAILAND) อ.ที่ปรึกษาวิทยานิพนธ์หลัก : รศ. ดร. นันทนา คชเสนี, อ. ที่ปรึกษาวิทยานิพนธ์ร่วม: Prof. Dr. Davey Jones, ดร. อัศมน ลิ่มสกุล, 173 หน้า.

การบริการเชิงนิเวศที่สำคัญประการหนึ่งของระบบนิเวศริมน้ำเขตร้อน คือการบรรเทาการปนเปื้อนแอมโมเนียม ไนเตรท และฟอสเฟต ในแหล่งน้ำโดยการชะละลายจากพื้นที่เกษตรกรรม อย่างไรก็ตามผลกระทบด้านลบของการทำหน้าที่ในระบบนิเวศดังกล่าวอาจเป็นแหล่งปลดปล่อยไนตรัสออกไซด์ การศึกษานี้มีวัตถุประสงค์เพื่อตรวจวัดการปลดปล่อยไนตรัสออกไซด์จากระบบนิเวศริมน้ำเขตร้อนเปรียบเทียบตามฤดูกาล ระหว่างฤดูฝนและฤดูแล้งและการใช้ที่ดินระหว่างป่าปลูกพืชตระกูลถั่ว, *Samanea saman* (Jacq.) Merr กับพื้นที่เกษตรกรรมแบบดั้งเดิมปลูกข้าวโพด, *Zea mays* L ที่มีการใส่ปุ๋ยไนโตรเจน และบ่งชี้ถึงปัจจัยควบคุมการปลดปล่อยไนตรัสออกไซด์ในระบบนิเวศดังกล่าว ผลการศึกษาพบว่าอัตราการปลดปล่อยไนตรัสออกไซด์รายปีของป่าปลูก (3.3 กิโลกรัมไนโตรเจนต่อเฮกแตร์ต่อปี) มีมากกว่าพื้นที่ปลูกข้าวโพด (2.2 กิโลกรัมไนโตรเจนต่อเฮกแตร์ต่อปี) อย่างมีนัยสำคัญ ($P<0.05$) อัตราการปลดปล่อยไนตรัสออกไซด์ในฤดูฝนมีมากกว่าฤดูแล้งอย่างมีนัยสำคัญ ($P<0.05$) การผันแปรของอัตราการปลดปล่อยไนตรัสออกไซด์มีความสัมพันธ์กับปัจจัยควบคุมการปลดปล่อยไนตรัสออกไซด์ได้แก่ ปริมาณน้ำในช่องว่างดิน ดีไนตริฟิเคชั่น และมวลชีวภาพคาร์บอนจุลินทรีย์ เมื่ออนินทรีย์สารไนโตรเจนและอินทรีย์สารคาร์บอนในดินมีเพียงพอ ปริมาณน้ำในช่องว่างดินมีบทบาทสำคัญในการควบคุมการปลดปล่อยไนตรัสออกไซด์ด้วยดีไนตริฟิเคชั่น อัตราการปลดปล่อยไนตรัสออกไซด์ตามระยะห่างจากแม่น้ำของการใช้ที่ดินแบบผสม ในฤดูฝนและแล้งมีความแตกต่างกันอย่างมีนัยสำคัญ ($P<0.05$) การปลดปล่อยไนตรัสออกไซด์เพิ่มมากขึ้นเมื่อจุดเก็บตัวอย่างอยู่ใกล้กับแม่น้ำ รูปแบบการปลดปล่อยไนตรัสออกไซด์ดังกล่าวสัมพันธ์เชิงผกผันกับปริมาณการลดลงของอินทรีย์สารคาร์บอนละลายน้ำ และอนินทรีย์สารไนโตรเจนจากพื้นที่เกษตรกรรมตอนบนสู่พื้นที่ริมน้ำตอนล่าง ในทางกลับกันปริมาณน้ำในช่องว่างดิน และดีไนตริฟิเคชั่น เพิ่มขึ้นเมื่อระยะทางของจุดเก็บตัวอย่างอยู่ใกล้กับแม่น้ำ แบบจำลองคอมพิวเตอร์ DeNitrification-DeComposition (DNDC) ประมาณการปลดปล่อยไนตรัสออกไซด์จากพื้นที่ปลูกข้าวโพดมีค่าต่ำกว่าการตรวจวัดภาคสนาม ปัจจัยที่มีผลต่อความไวของการปลดปล่อยไนตรัสออกไซด์ด้วยแบบจำลองคอมพิวเตอร์ DNDC ได้แก่ อินทรีย์สารคาร์บอน ปริมาณน้ำในช่องว่างดิน และปริมาณการใช้ปุ๋ยไนโตรเจนตามลำดับ เมื่อเปรียบเทียบอัตราการปลดปล่อยไนตรัสออกไซด์รายปีของป่าปลูกในระบบนิเวศริมน้ำเขตร้อนมีค่าไม่แตกต่างจากป่าไม้ในระบบนิเวศริมน้ำเขตอบอุ่นและระบบนิเวศบก แม้ว่าการปล่อยไนตรัสออกไซด์จากพื้นที่ปลูกข้าวโพดมีค่าใกล้เคียงกับระบบนิเวศริมน้ำเขตอบอุ่น แต่มีค่าสูงกว่าระบบนิเวศบกอื่นๆ ผลการศึกษานี้บ่งชี้ว่าระบบนิเวศริมน้ำเขตร้อนที่มีพื้นที่เกษตรรายล้อมมิได้เป็นแหล่งปลดปล่อยไนตรัสออกไซด์ที่สำคัญ และไม่มีผลลดทอนต่อการทำหน้าที่ให้ผลตอบแทนจากการบริการเชิงนิเวศได้

สาขาวิชา วิทยาศาสตร์ชีวภาพ ลายมือชื่อนิสิต
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5073907723 : MAJOR BIOLOGICAL SCIENCES
KEYWORDS: TROPICAL RIPARIAN ECOSYSTEM / NITROUS OXIDE EMISSION / NITROGEN CYCLING / FERTILIZER / LAND USE

BOONLUE KACHENCHART: SEASONAL NITROUS OXIDE EMISSION FROM DIFFERENT LAND USE IN TROPICAL RIPARIAN ECOSYSTEM: A CASE STUDY IN NAN PROVINCE, NORTHERN THAILAND. ADVISOR: ASSOC. PROF. NANTANA GAJASENI, Ph.D., CO-ADVISORS: PROF. DAVEY JONES, Ph.D., ATSAMON LIMSAKUL, Ph.D., 173 pp.

One of an important ecological services provided by tropical riparian ecosystems is the mitigating contamination of ammonium, nitrate, and phosphate leaching from agricultural area to water resources. However, a negative impact of this pollutant remediation may be that the ecozone also functions as a source of nitrous oxide (N_2O) emission. The objectives of this study were to measure the N_2O emission in such an ecosystem with specific emphasis on temporal aspects; comparing between wet and dry seasons and different land use; comparing a leguminous reforestation, *Samanea saman* (Jacq.) Merr, with applied nitrogen fertilizer in conventional agriculture with maize, *Zea mays* L, and to identify the major drivers controlling these emission. The results revealed that the annual average emission of N_2O from the reforestation (3.3 kg N_2O-N ha^{-1} y^{-1}) was significantly higher than the agricultural areas with maize (2.2 kg N_2O-N ha^{-1} y^{-1}) ($P < 0.05$). The rate of N_2O flux in the wet season was higher than in the dry season ($P < 0.05$). The N_2O emission variability was correlated with the controlling factors; water filled pore space (WFPS), denitrification, and microbial biomass carbon. When inorganic nitrogen and soil organic carbon are sufficient, WFPS plays an important role in controlling N_2O emission contributed by denitrification. N_2O flux observed by distal proximity to river in a mixture transect was significantly different both wet and dry seasons ($P < 0.05$) in that N_2O flux increased where sampling locations were closed to river. This pattern was correlated to the slowly decreasing amounts of inorganic nitrogen and dissolved organic carbon from upper agricultural field boundary to lower river side. Conversely, WFPS and denitrification increased in the opposite patterns of those relationships. N_2O flux from maize area simulated by the DeNitrification-DeComposition model (DNDC) was underestimated when validated with those observed from filed experiment. Sensitivity analysis indicated that N_2O emission variability by DNDC model was dependent on soil organic carbon, WFPS, and nitrogen input to maize plot, respectively. Comparatively, annual N_2O emission from the reforestation in the tropical riparian zone was similar to those reported for temperate riparian zones and other ecosystems. Although the annual N_2O flux from the agricultural area with maize is comparable to other riparian ecosystems, it is higher than those of other N_2O flux from terrestrial zones. The results suggest that tropical riparian ecosystem surrounding agricultural land does not represent a major hotspot of N_2O flux and does not diminish the positive benefits which they provide in relation to other aspects of ecosystem service provision.

Field of Study : Biological Sciences Student's Signature ....
Academic Year : 2011 Advisor's signature ....
Co-advisor's signature ....
Co-advisor's signature ....

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Lastly, and most importantly, I wish to express my gratitude and thanks to my parents. To them I dedicate this thesis.

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ABBREVIATIONS

DNDC	DeNitrification DeComposition
DOC	Dissolved organic carbon
GHGs	Greenhouse Gases
IPCC	Intergovernmental Panel on Climate Change
MBC	Microbial biomass carbon
N	Nitrogen
N_2O	Nitrous oxide
NH_4^+	Ammonium
NO_3^-	Nitrate
TN	Total nitrogen
TOC	Total organic carbon
WFPS	Water filled pore space

CHAPTER I

INTRODUCTION

1.1 Overview of the study

Nitrous oxide (N_2O) is one of the greenhouse gases (GHGs) contributing around 7.9% of the global annual anthropogenic GHGs emissions. N_2O has a long atmospheric residence time about 114 years, while the residence time in the atmosphere of CO_2 and CH_4 is around 100 and 12 years, respectively. Moreover, N_2O entails in the catalytic destruction of stratospheric ozone. Atmospheric concentration of N_2O has risen 16% from 270 ppb to 319 ppb during pre-industrial era and the year 2005 (IPCC, 2007). At present, N_2O emission from agroecosystems represent approximately 60% of all anthropogenically-derived N_2O emissions (Smith et al., 2007). The flux of N_2O varies in different ecosystems. In temperate agricultural systems, measured N_2O emission in maize field from 35 studies was 0.5-7.3 % of N applied (Mosier et al., 2004). On the contrary, N_2O emission by denitrification in maize fields in subtropical agricultural systems in Pakistan was about 40% of N applied (Mosier et al., 2004). In Thailand, N_2O emission from maize fields increased 47–75 kg N ha^{-1} or average 0.1–0.4 percentage due to applied N-fertilization (Watanabe et al., 2000).

Riparian ecosystem is a trans-boundary zone in which aquatic ecosystem is adjacent to terrestrial ecosystem (Naiman et al., 2005). The riparian ecological functions serve a function for filtering sediments and nutrients before leaching them into water body, thus enhancing water quality. On the other hand, due to high water content of anoxia, nitrate, and organic matter as substrates in denitrification process, riparian zone is the hot spot of N_2O source (Hefting et al., 2003). It has been suggested that indirect N_2O emission estimated by Intergovernmental Panel on Climate Change (IPCC) has to distinguish between agricultural upland and riparian buffer zone in landscape obtaining enormous N input (Hefting et al., 2006). Therefore, nitrate loading from lateral process in adjacent ecosystems from upland to aquatic systems enhances denitrification and nitrification in riparian zone.

Effect of seasonal variation in plant production and temperature together with seasonal fluctuations in water table depth is likely to lead to significant temporal variation of N_2O fluxes in riparian zones. For example, dry warm season can stimulate organic matter breakdown and NO_3^- production, while the start of the subsequent wet season may induce the loss of N_2O when water logging occurs (Dalal et al., 2003). GHG emissions from these neighboring agricultural areas may also be indirectly affected by riparian areas due to the influence of hydrological flow and water table depth (Naiman et al., 2005). Spatial variation of land use change affects the N_2O emission. Land use change from natural pastures to agricultural areas with intensive applied nitrogen fertilizer and practices increase N_2O flux more than that observed in undisturbed pastures. For example, long term study on paired forest and pasture sites on a clay textured Oxisol, Brazil, N_2O emissions from a 3-year-old pasture were 3 times greater than that of the nearby mature forest. In short, the increase of N_2O emission in land use change may be transitory (Erickson and Keller, 1997). Another example, cultivated and uncultivated wetlands in central Saskatchewan, Canada, emitted significantly different N_2O in the same period; 112.8 to 17.0 ng N_2O m^{-2} s^{-1} and 31.8 to 51.1 ng N_2O m^{-2} s^{-1}, respectively (Bedard-Haughn et al., 2006). Besides, changing peat land into cultivated upland and paddy field can increase the N_2O emission because of the alternation of water table in dry season, soil moisture contents, and the addition of ammonium fertilizer or C from rice straw (Hadi et al., 2000). The variability of nutrient concentrations and physical factors found in riparian zone is the consequence of spatial heterogeneity. Lateral transfer and spatial proximity to river also affect nutrient concentration and flow in riparian zone (Fisher and Welter, 2005). Spatial arrangement of land use types would intercept the sediments from runoff and increase the retention time of nitrate leaching in shallow ground water. It is suspected that high nitrate concentration is the source of nitrogen reduction to be N_2O. For example, nitrate concentration in riparian forest zone closed to river is likely lower than that of the adjacent to upper zone in the agricultural area because it is reduced to be N_2O and N_2 by denitrificaiton (Hefting et al., 2003). The major mechanism N_2O formations are attributed by the biological nitrification, denitrification, and nitrifier denitrification processes (Schipper et al., 1993; Ambus, 1998; Wrage et al., 2001). Both nitrification and denitrificaiton are controlled by the water filled pore space (Bateman and Baggs, 2005), available inorganic N (Mosier et al., 1983), and carbon content (Drury and McKeeney, 1991). Such matters and condition are intensively observed in riparian zone. Despite their potential importance, there are few reports of the N_2O production in riparian systems worldwide and none in the tropics. Along the Nan River area, Nan province, Thailand is subjected to the ecosystem change from forest ecosystem to maize field and the introduction of intensive chemical N fertilizers about 186.25 kg N ha^{-2} $year^{-1}$ (ONEP, 2004). In addition, this area defined as riparian ecosystem, is suspected as a N_2O emission source due to adding nitrate and water content, high organic carbon, and anaerobic environment from stream and upland areas. It can accelerate both nitrification and denitrification processes.

The goal of this research is to evaluate the N_2O emission and quantify the change in N_2O emission in tropical riparian zone in terms of spatial variations (i.e. different land uses), temporal changes (i.e. wet and dry season), and landscape arrangement and spatial proximity in tropical riparian zone. This should be corresponding to the theoretical realm of N_2O emission, the understanding of the source and factors controlling N_2O emission, and simulated N_2O emission to landscape scale by process-based modeling to develop management practices to minimize N_2O emission from the managed ecosystems.

1.2 Scope of the study

The research describes the variation of N_2O emitted from tropical riparian zone as the consequence of spatial variability (i.e. reforestation and maize with applied high rate of nitrogen fertilizer), temporal scale (i.e. wet and dry seasons, spatial proximity to River (variability of N_2O emission and the controlling factors across lateral transfers), and the environmental factors controlling nitrification and denitrification. Moreover, this study involving nitrogen and carbon pools and agricultural practices can be used to simulate the N_2O flux by process based models. The study established the experimental study sites in tropical riparian zone along the Nan River, Nan province, Northern Thailand. The scope of the study applied a system approach for designing experimental workflow and collected parameter was summarized as follows in figures 1.1 and 1.2.

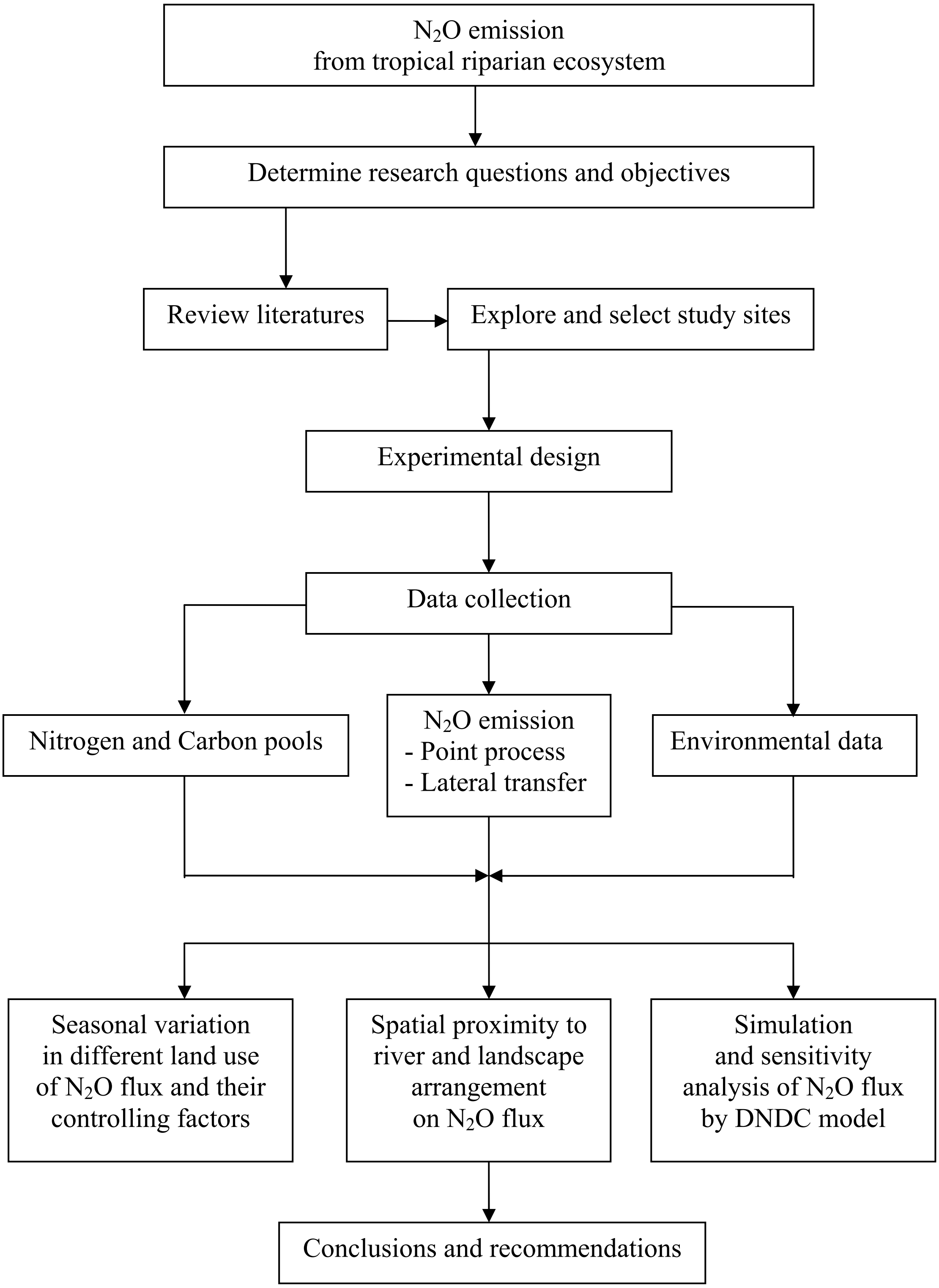


Figure 1.1 Scope of the study

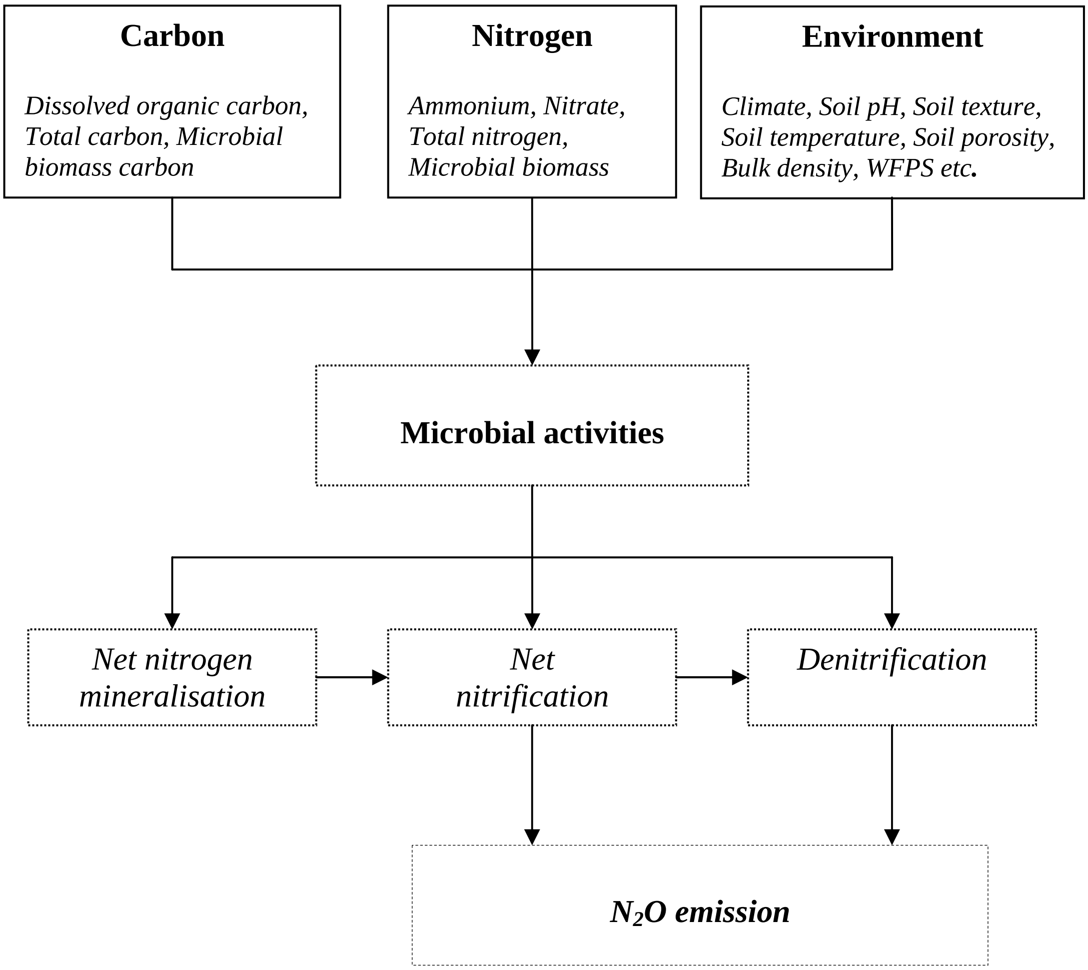


Figure 1.2 System of experimental workflow and collected parameters; solid line box present input, dotted line box present process, and long dash line text present out put. *Intalic* letter present parameters collected in this study.

1.3 Objectives

1.3.1 To measure the N_2O emission from tropical riparian zone along the Nan River that is exposed to different seasons and land use and environmental gradients due to point process and lateral transfer process;

1.3.2 To study the key mechanisms of N_2O emission; denitrification and nitrification;

1.3.3 To study the relationship between the controlling factors and N_2O flux;

1.3.4 To simulate N_2O emission by process-based modeling of DeNitrification-DeComposition model (DNDC) model using the controlling factors and environmental data.

1.4 Research questions

1.4.1 How much seasonal N_2O does a tropical riparian ecosystem emit from different land use and the effect of proximate sampling location to river?

1.4.2 Are there N_2O flux spatial and seasonal variability?

1.4.3 What are the environmental factors controlling N_2O emissions and how are they related?

1.4.4 What is the difference of the N_2O emission rate among tropical riparian ecosystems, riparian temperate zones, and other ecosystems?

1.4.5 Is it possible to use soil properties and environmental conditions to simulate N_2O flux?

1.5 Organization of dissertation

This dissertation comprises of seven chapters as follows:

1.5.1 Chapter I is an introduction to describe the overview and scope of the study, objectives, and an organization of this thesis.

1.5.2 Chapter II reviews the previous study from various sources in order to gain better understanding and indentify the knowledge gap of N_2O emission from various ecosystems and agricultural systems. Also, the review covers the elementary topics of this research such as the properties and function of riparian ecosystems, riparian ecosystem in Thailand, N_2O formation mechanism and factors affecting nitrification, denitrification, and N_2O emission.

1.5.3 Chapter III describes the study sites, experimental design to measure N_2O emission and their controlling factors. This chapter also depicts the protocol for collecting and analyzing various parameters.

1.5.4 Chapter IV describes the N_2O emission rate from tropical riparian system in which the seasonal variation in different land use type (reforestation and agricultural area with maize) was experiments. This chapter describes the controlling factors that affect N_2O emission and comparing the N_2O flux from different land uses from other ecosystems.

1.5.5 Chapter V describes the significant difference of N_2O emission on proximity to river of each sampling plot. The chapter also describes the spatial variation of the controlling factor concentrations as a consequence of lateral transfer from upland to lower land closed to river.

1.5.6 Chapter VI describes the use of controlling factors and climatic data to simulate N_2O emission by process based model software. The N_2O emission obtained from simulation was validated by N_2O emission observed in filed experiments. The sensitivity analysis also explains the critical level of input parameters to simulate N_2O emission.

1.5.7 Chapter VII is the conclusion and recommendation. The results are synthesized to develop alternative management practice to minimize N_2O emission from managed ecosystems.

CHAPTER II

LITERATURE REVIEWS

2.1 Nitrous oxide emission

2.1.1 Global nitrous oxide emission budget

Greenhouse gases (GHGs): carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are playing a crucial role to increase global temperature. The radiative forcing mostly occupies the proportion of anthropogenic GHG emission when compared with industrial GHGs such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). N_2O has a long atmospheric residence time about 114 years, while those of CO_2 and CH_4 are about 100 and 12 years, respectively. Furthermore, N_2O is involved in the catalytic destruction of stratospheric ozone depleting by nitric oxide (NO) and nitrogen dioxide (NO_2). Atmospheric concentrations of N_2O have risen 16% from 270 ppb to 319 ppb during pre-industrial era and 2005. The sources of N_2O emitted to the atmosphere from human activities are equal to those in natural system. N_2O mixing ratio of dry air during 40 years from1960 to 1999 rose in an average of at least two times more than that of the two millennia around AD 1850. Global N_2O emissions increased from 11 Tg N yr^{-1} in 1850 to 15 Tg N yr^{-1} in 1970 and to 18 TgNyr^{-1} in 1994 due to the extension of agricultural area and intensive agricultural practices with enhanced use of nitrogen fertilizer (Kroeze et al., 1999).

N_2O emissions to the atmosphere from natural sources include oceans, ammonia oxidation in the atmosphere, and soils especially tropical soil. Also, the anthropogenic sources are fossil fuel combustion, industrial processes, agriculture and river, estuaries, and coastal zones. Interestingly, atmospheric N_2O concentrations have been increasing since the industrial revolution and currently account for 6% of the total anthropogenic radiative forcing due to applied synthetic nitrogen fertilizer in agriculture (Davidson, 2009). From Table 2.1, total average of the global nitrous oxide emission sources is 17.7 Tg N yr^{-1}. They are divided as anthropogenic source and natural source of about 6.7 Tg N yr^{-1} and 11.0 Tg N yr^{-1}, respectively. The agriculture and soil under vegetation are the highest emission proportions of each source with average of 2.8 Tg N yr^{-1} and 6.6 Tg N yr^{-1}. The former contributes through the intensive use of nitrogen fertilizer (Davidson, 2009), while the latter contributes largely from tropical wet forest, tropical dry savannas, temperate forest and temperate grassland (Mosier et al., 1998).

Table 2.1 Global nitrous oxide emission (Tg N yr^{-1}) for the 1990s.

Source	**TAR (2001)**	**AR4 (2007)**
Anthropogenic sources		
Fossil fuel combustion & industrial processes	1.3[a]/0.7[b] Range 0.2-1.8	0.7 Range 0.2-1.8
Agriculture	6.3[a]/2.9[b] Range 0.9-17.9	2.8 Range 1.47-4.8
Biomass and biofuel burning	0.5[a] Range 0.2-1.0	0.7 Range 0.2-1.0
Human excreta	-	0.2 Range 0.1-0.3
River, estuaries, coastal zones	-	1.7 Range 0.5-2.9
Atmospheric deposition	-	0.6 Range 0.3-0.9
Anthropogenic total	8.1[a]/4.1[b]	6.7
Natural sources		
Soils under natural vegetation	3.0[a]/6.6[b] Range 3.3-9.9	6.6 Range 3.3-9.0
Oceans	3.0[a]/3.6[b] Range 1.0-5.7	3.8 Range 1.8-5.8
Atmospheric chemistry	0.6[a] Range 0.3-1.2	0.6 Range 0.3-1.2
Natural total	9.6[a]/10.8[b]	11.0
Total sources	17.7[a]/14.9[b] Range 5.9-37.5	17.7 Range 8.5-27.7

Note: TAR is Third Assessment Report of IPCC (2001). AR4 is The Fourth Assessment Report of IPCC (2007). N_2O emission in TAR column is adapted from Mosier et al. (1998) and Kroeze et al. (1999) and Olivier et al. (1998) is represented in a and b super subscription. Source: adapted from Smith et al. (2007).

2.1.2 N_2O flux from agricultural soils and uncertainty

N_2O emissions from agroecosystems represent ca. 60% of all human activities deriving N_2O emissions (Smith et al., 2007). However, global soils under agricultural sector contributing N_2O emission, especially in tropical zone, have high uncertain estimation (Lokupitiya and Paustian, 2006). For example, N_2O flux from agriculture on global scale in 1990s varied from 0.9-4.8 Tg N yr^{-1} (Smith et al., 2007), 0.6-14.8 Tg N yr^{-1} (Mosier et al., 1998) to 5.3 Tg N yr^{-1} in 2006 (Syakila and Kroeze, 2011).

Bowden (2000) reported that uncertainty in the mass balance of the atmospheric N_2O budget was around 30%. Smith et al. (2010) discussed that IPCC concerning the N_2O emission from agriculture is in high uncertainty with the range of 0.01-2.2 Tg N yr^{-1} in 1990 and 0.03-3.3 Tg N yr^{-1} in 1992. These uncertain estimates were two orders of magnitude from various site measurements in different environmental conditions such as using nitrogen fertilizer and water irrigation. The variability of N_2O flux may be a consequence of bottom up approach estimation that the data from various experiment N_2O observation and process based model at local scale with different environmental conditions. Such studies with different spatial-temporal scales were also complied with global N_2O emission. Therefore, the assessments of N_2O have been changed over time in order to cover all emission sources and scientific evidences (Table 2.2). The N cycle dynamic is also the cause of uncertainty. N mineralization occurs rapidly that it is unpredictable for the rate of N_2O production in micro scale by microbial activity in various ecosystems.

Syakila and Kroeze (2011) gave the reason to revise the global N_2O emission by accounting the downward emission factor for agriculture, increasing the role of atmospheric deposit in ocean, and balancing the source and sink during N_2O formation by the reduction to N_2 in soil-aquatic system. Soil aquatic system: wetland, riparian zone, and peat land as the sources of N_2O emission would be accounted for national GHG inventory due to the hotspot of N_2O formation by biological nitrification and denitrification (Groffman et al., 2000; Hefting et al., 2003; Bedard-Haughn et al., 2006).

Table 2.2 Estimation of global N_2O emission from agriculture from 1990 to 2011

Author and year	**Global N_2O flux ($Tg\ N\ yr^{-1}$)**	**Emission sources**
IPCC (1990)	0.01-2.2	Fertilizer and groundwater
IPCC (1992)	0.03-3.0	Cultivated soil
IPCC (1996)	3.5 (1.8-5.3)	Fertilizer, animal waste and N-fixation
Mosier et al. (1998)/ IPCC (2001)	6.8 (1.0-18.9)	Fertilizer, N-fixation, indirect emission, manure management, and biomass burning
IPCC (2007)	2.8 (1.47-4.8)	Fertilizer, indirect emission, manure management, and biomass burning
Syakila and Kroeze (2011)	5.3	Fertilizer, indirect emission, manure management, and biomass burning, ocean and soil-aquatic system

Source: modified from Smith et al. (2010).

2.1.3 Riparian wetland as the hotspot of N_2O emission

Riparian zones are transitional semi terrestrial area influenced by water, extending from the edges of water bodies to the edges of upland area (Naiman et al., 2005). The riparian ecosystem functions as habitat and biodiversity hot spot; protects aquatic ecosystem; and provides human use values. The characteristics of riparian zone are distribution in all stream orders lying along river or water body, high groundwater level supported by stream, effecting by freshwater or flood but not submerged by water unlike wetland, wet soil, high soil water content and water level in summer season, more minerals and organic matter, plants adapted to wet soil, and high productivity and litter fall rate.

The ability of riparian buffer strip is well known to improve water quality by reducing nitrate leaching and sediment before loading into water body and groundwater by plant uptake, water dilution, microbial immobilization and denitrification (Hefting et al., 2003). However, significant losses of N could occur via denitrification, thus making riparian zones potential hotspots of N_2O emission due to high potential for reducing conditions (high water content, nitrate, and organic matter) to prevail in riparian soils (Groffman et al., 2000; Hefting et al., 2003; Vellidis et al., 2003; Verhoeven et al., 2006). So, riparian wetlands provide environmental benefits to reduce agricultural impacts on water quality, but they may also induce N_2O emission to atmosphere called pollution swapping (Dhondt et al., 2004). Especially, in agricultural area located in riparian zone, there is high application rate of nitrogen fertilizer and lateral flow on river side, thus carrying N excess towards to streams. The direct emission is the rate of used N fertilizer and manure, while the indirect emission occurs as N transferred by oxidation and reduction state, nitrate leaching and runoff, and atmospheric deposition (Mosier et al., 1998). In riparian zone, both direct and indirect N_2O emissions take place simultaneously. Rapid N cycle processes in which high nitrate concentration from applied fertilizer or manure in agricultural field may induce indirect high rate of N_2O flux. In the Netherlands, nitrate leaches into riparian up to 470 g N m^{-2} yr^{-1}. N_2O emissions in forest buffer zone and grassland buffer zone are 20 Kg N ha^{-1} yr^{-1} and 2-4 kg N ha^{-1} yr^{-1}, respectively (Hefting et al., 2003). Nitrate loading from lateral process as adjacent ecosystems from upland to aquatic systems enhances denitrification activity in riparian zone. For instance, N_2O emissions from riparian forest soils exposed to prolonged nutrient runoff from plant nurseries compared with those of similar forest soils not exposed to nutrient runoff, net N_2O emissions in the N-exposed sites was 1.5 and 1.7 times higher than those of the non-exposed sites at 30 and 60 µg NO_3^-N g^{-1} soil amendment rates, respectively (Ullah and Zinati, 2006).

The indirect estimated N_2O emission by Intergovernmental Panel on Climate Change (IPCC) distinguished between agricultural upland and riparian buffer zone in landscape obtaining enormous N input (Hefting et al., 2006). This research is relevant to the Nevison's review (2000). N_2O emission from indirect estimation from leaching and runoff accounts for about 75%, hence leading to uncertain assessment. Aquatic system is the unique landscape that contributes mainly indirect agricultural N_2O emissions because there is much of nitrogen leaching and runoff from agricultural land through groundwater, rivers, lakes and estuaries (Seitzinger et al., 2000). The magnitude of both direct and indirect N_2O emissions may be increased if agricultural areas are located in riparian ecosystem. It seems that the assessment of N_2O emissions from riparian ecosystem will not only reduce the uncertainty associated with indirect agricultural sources (Cooke et al., 2008), but also lessen the uncertainty in the mass balance of the atmospheric N_2O budget below 30% (Bowden et al., 2000).

2.1.4 Agricultural N_2O flux of Thailand

Thailand greenhouse gas inventory (ONEP, 2010) reported that total N_2O emission in 2000 from agricultural sector was 24.51 Gg N_2O. The direct emission is 17 Gg N_2O, while indirect emission is 7.51 Gg N_2O (Table 2.3). N_2O emission from grazing animal, chemical fertilizer and those from leaching and runoff are 27.70%, 27.33%, and 18.85%, respectively. Interestingly, total nitrogen loss after applying synthetic N via leaching and runoff process from 2000 to 2004 ranged from 230,252 to 248,998 ton. It indicates that the nitrification and denitrification process of the N cycle are crucial to contribute N_2O emission.

Table 2.3 Thailand's N_2O emissions in 2000 compared with INC and SNC in 1994

Categories	**Emission in Gg N_2O**		
	1994 INC	**1994 SNC**	**2000 SNC**
1. Direct emission			
1.1 Chemical fertilizer	6.80	5.48	6.70
1.2 Manure application to soil	4.75	2.54	2.48
1.3 N fixation crop	(0.55)	(0.55)	0
1.4 Crop residue application	2.29	0.01	1.03
1.5 Compost application	(0.08)	(0.08)	0
1.6 Grazing animal	10.11	11.52	6.79
Subtotal 1	23.95	19.55	17.00
2. Indirect emission			
2.1 Emission from atmospheric deposition of NOx and NH_3	2.64	2.83	2.89
2.2 Emission from leaching and runoff	8.13	3.87	4.62
Subtotal 2	10.77	6.7	7.51
Total	34.72	26.25	24.51

Note: Initial National Communication in 1994 (1994 INC) and Second National Communication in 1994 (1994 SNC) shared the same data, but the estimations were different emission factors. Source: ONEP (2010).

Total N_2O emission during 2000 and 2004 has increased every year except in 2004. The rate of total N_2O emission between 2000 and 2004 is increased by 2.72 %. The direct emission contributed 70% of total N_2O emission (Table 2.4). Due to the difference of Emission Factor (EF) to estimate N_2O emission, the percentage of uncertainty is very high in some subcategories. For example, emission from grazing animal, manure application to soil, chemical fertilizer, and leaching and runoff were 218%, 183%, 183%, and 40%, respectively.

Table 2.4 Total N_2O emission of Thailand 2000-2004

	Emission in Gg N_2O				
Categories	**2000**	**2001**	**2002**	**2003**	**2004**
1. Direct emission					
1.1 Chemical fertilizer	6.70	6.69	6.86	7.25	6.55
1.2 Manure application to soil	2.48	2.67	2.49	2.74	2.24
1.3 Crop residue application	1.03	1.05	1.05	1.16	1.12
1.4 Grazing animal	6.79	7.19	7.37	7.79	8.16
Subtotal 1	17.00	17.6	17.77	18.94	18.07
2. Indirect emission					
2.1 Emission from atmospheric deposition of NOx and NH_3	2.89	3.03	3.05	3.25	3.03
2.2 Emission from leaching and runoff	4.62	4.81	4.84	5.12	4.78
Subtotal 2	7.51	7.84	7.89	8.37	7.81
Total	24.51	25.44	25.66	27.13	25.88

Source: ONEP (2010)

The flux of N_2O varies in different ecosystems. In temperate maize agricultural systems, its measurement of N_2O emissions from 35 studies is 0.5-7.3 % of N applied (Mosier et al., 2004). On the contrary with subtropical agricultural systems in Pakistan, N_2O emission by denitrification in maize field is about 40% of N applied (Mosier et al., 2004). In the areas located in the tropical zone of Thailand, N_2O emission from maize fields increases 47–75 kg N ha^{-1} due to N-fertilization or an average of 0.1–0.4 percentage of applied fertilizer, and the rate of N_2O emission were 4.16±1.52, 5.05±1.65, 5.25±1.68 and 6.74±2.95 μg N m^{-2} h^{-1} (Watanabe et al., 2000). Monthly average N_2O fluxes from natural tropical forest soil in Thailand are 13.0±8.2 μg N m^{-2} h^{-1} for dry evergreen forest, 5.7±7.1 μg N m^{-2} h^{-1} for hill evergreen forest, 1.2±12.1 μg N m^{-2} h^{-1}for moist evergreen forest, 7.3±8.5 μg N m^{-2} h^{-1}for mixed deciduous forest and 16.7±9.2 μg N m^{-2} h^{-1} for acacia (Vanitchung et al., 2011). High variation of N_2O flux is inevitable due to different environmental conditions, so the question is not on huge amounts of gas emitted. However, understanding of what factors controlling the N_2O flux could be useful to mitigate the impact of gas emissions into the atmosphere.

2.2 Nitrous oxide formation

N_2O emission in soil is mainly formed by biological processes with N_2O-genic enzymes of bacteria, while archaea and fungi are also involved but presently unclear (Baggs and Philippot, 2010). The biological processes producing N_2O (Figure 2.1) include nitrification (nitrification and nitrifier denitrification) and nitrate dissimilation (denitrification and nitrate ammonification). However, N_2O is produced mainly from the denitrification and nitrification (Stevens et al., 1997). The remaining biological processes producing N_2O are published by a few studies and their mechanisms are not clear (Baggs, 2008).

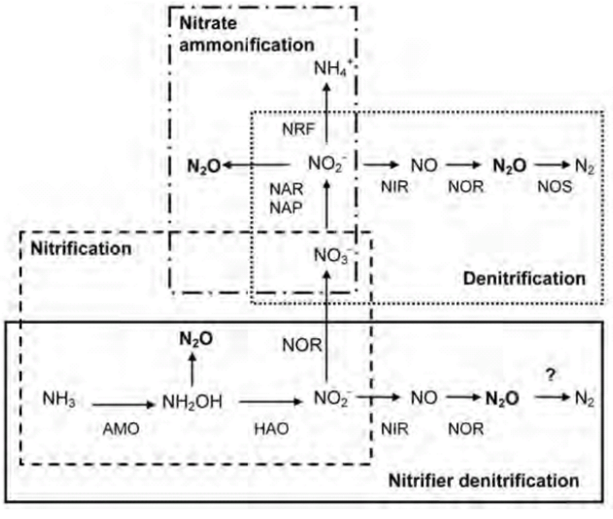


Figure 2.1 N_2O formation pathways in soil involving microbial activities (Baggs, 2008).

2.2.1 Nitrification

Nitrification is the series of conversion of ammonia, nitrite, and nitrate by ammonia-oxidizing bacteria (AOB) under aerobic condition (Figure 2.2). There are 2 sub processes. Firstly, ammonia (NH_3^-) is oxidized to hydroxylamine (NH_2OH) by mono-oxygenase enzyme (AMO) and then hydroxylamine is oxidized to nitrite by hydroxylamine oxidoreductase by *Nitrosomonas* spp. The N_2O formation takes place in this process. After that nitrite is oxidized to nitrate by nitrite oxidoreductase (NOR) in *Nitrobactor* spp. These pathways require four electrons to balance equation. First two electrons are demanded during the oxidation of ammonia oxidation to hydroxylamine. Other two electrons are used to produce energy and oxygen reduction to water (Galloway, 2005).

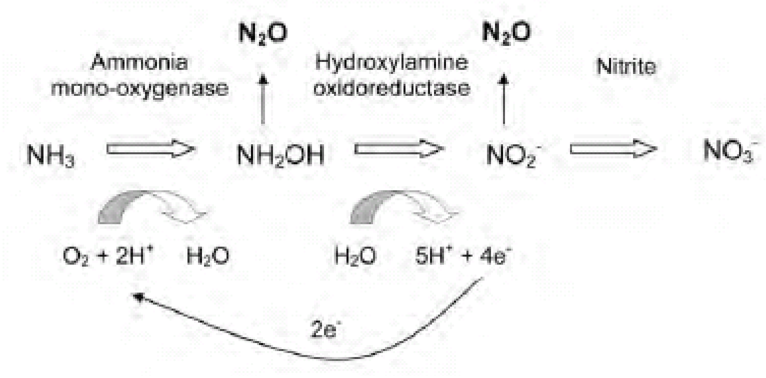


Figure 2.2 N_2O productions during nitrification pathway (Baggs and Philippot, 2010)

2.2.2 Denitrification

Denitrification is the reduction of NO_3^- to NO_2^-, NO, N_2O and N_2 . It is an anaerobic process and requires nitrate and organic matter. Microorganism uses nitrate as an oxidant to obtain energy from organic matter (Galloway, 2005). During the process, nitrate, nitrite, nitric oxide, and nitrous oxide are reduced by enzymes nitrate reductase (NAR), nitrite reductase (NIR), nitric oxide reductase (NOR) and nitrous oxide reductase (NOS), respectively.

2.2.3 Nitrate ammonification

After nitrification, nitrate is reduced to NO_2^- and NH_4^+. These processes occur together with a respiratory electron transport system to conserve energy and ATP synthesis. Gram-negative and Gram-positive bacteria are obligate anaerobes (e.g. *Clostridium* spp), facultative anaerobes (e.g. *Enterobacter* spp) and aerobes (e.g. *Bacillus* spp). The membrane-bound nitrate reductase (Nar) and the periplasmic nitrate reductase (Nap) are the enzyme catalyzed reduction of nitrate to nitrite. Then, nitrite is reduced to ammonium by ammonia cytochrome c nitrite reductase (NRfA). During these steps, N_2O can be produced (Baggs and Philippot, 2010).

2.2.4 Nitrifier denitrification

In the nitrification process, during the oxidation of NH_3 to NO_2^- by ammonia-oxidizing bacteria (AOB), some NO_2^- is reduced to N_2O and N_2 by the same enzyme in denitrification process (Wrage et al., 2001).

2.3 Factors controlling N_2O formation and emission

The N_2O can be produced in many nitrogen pathways. It is a competition among microorganisms that are active under suitable environment. To mitigate N_2O emission to atmosphere, it is necessary to understand the environmental factors that evolve mainly N_2O emission as the by-product of nitrification and denitrification.

2.3.1 Factors controlling nitrification

The rate of ammonia oxidation is influenced by ammonia availability, nitrifying bacteria population, pH, temperature, oxygen, soil moisture and soil texture (Sahrawat, 2008).

The nitrification rate is related to soil texture. Clay that has H^+ may decrease the ammonia retention time in soil due to the sorption between cations, while silt does not influence. Coupled with high clay percentage and moisture in soil, nitrifying bacteria are not easy to assimilate NH_4^+ if carbon as the energy source is lacking. Nitrification occurs in aerobic state that is near filled capacity moisture (-33 kPs) or when oxygen concentration of atmosphere about 20%, which is suitable for maximum rate of nitrifying bacteria. N_2O formation during nitrification is best occurred when there is highest available oxygen at water filled pore space about 35-60%. At ecosystem level, as expected, optimal soil texture, oxygen status, and soil water content can activate maximum nitrifying bacteria activity, thus create high rate of N_2O emission to atmosphere. In experimental study, soil temperature at 25ºC to 35ºC on bell-shape curve is responding to the optimal nitrification. At field experiment, nitrification is different in various climatic zones. For example, optimal temperature at 25ºC and 35ºC takes place at temperate and tropical soil, respectively. Interestingly, nitrifying bacteria of both climates may be able to adapt to the temperature. Also, $pH < 5.0$ inhibits nitrification process.

2.3.2 Factors controlling denitrification

Carbon is demanded for denitrification in soil as electron donors and the sources of cellular material. Sufficient C substrate can cause rapid O_2 consumption, thus amplifying the potential denitrification (Seitzinger, 1994). It is the fact that 1 µg of available soil organic carbon is required for production of 1.17 ug of N as N_2O or of 0.99 µg of N as N_2 (Burford and Bremner, 1975). The addition of organic materials such as plant residues or manure can increase denitrification rate. N_2O flux increases because soil has been obtained nitrogen after logging and been decomposed for one year (Yashiro et al., 2008). In riparian zone, the wood debris is carried from up stream and deposited (Naiman et al., 2005). Increasing soil depth more than 60 cm. restricts carbon availability, thus reducing denitrification activity (Rolston et al., 1976). The potential for denitrification is larger at soil depths < 30 cm (Bernal et al., 2007; Metay et al., 2007).

Nitrate acts as electron receptor in denitrification process. Fertilizer and manure applications affect N_2O emission (Mulvaney et al., 1997; Kaiser et al., 1998; Hellebrand et al., 2003; Silva et al., 2008) depending more especially on the type of N source including NO_3^-, NH_4^+ or organic N (Dambreville et al., 2008). For example, the mean annual N_2O emissions from the annual plants that added calcium ammonium nitrate fertilizers and wood ash at 0, 75 and 150 kg N ha^{-1} are more than twofold greater than those of perennial plants (4.3 kg ha^{-1} vs. 1.9 kg ha^{-1}). Fertilizer used in producing N_2O contributed about 32% to 67% of the total soil N_2O flux (Kavdir et al., 2008).

Oxygen in soil pore also controls denitrification process. Oxygen in soil completely inhibits denitrification activity in oxic conditions (20% oxygen); denitrification enzyme activity is activated up to two times at the wet site compared with the dry site (Burgin et al., 2010). Soil denitrifying population in wastewater treatment systems appears to be limited by soil aeration, and limiting oxygen availability increased the denitrifying population above that observed in the field (Barton et al., 2000).

Soil water content affected denitrification process by supporting anaerobic conditon that is suitable for microbial activities; inhibiting O_2 diffussion to soil pores; delivering organic carbon and inorgnaic nitrogen via wet and dry cycles; and providing as solubal reagents that can exchange substrates between soil and microorganisms (Pathak, 1999).

High N_2O emissions are a result of denitrification and occurs at the water filled pore space (WFPS) >= 70%, and N_2 production occurs only at the highest soil moisture level (>=90% WFPS) but it is considerably lesser than the N_2O emission (Ruser et al., 2006). So, water filled pore space, compared with soil water content, and its reliability are used as an indicator of reduced aeration dependent denitrification for soils of various texture (Aulakh et al., 1991). Hence, avoiding wet soil conditions (>60% WFPS) and applying NO_3^- form of N fertilizer would reduce potential N_2O emissions from arable soils (Liu et al., 2007).

Soil pH controls N_2O emission from denitrification depending differently on the diversity and life cycle of the microorganism and nitrate availability, which the pH for denitrifying bacteria growth is between 6 and 8. (Pathak, 1999; Šimek and Hopkins, 1999).

Soil redox potential (Eh) is the indicator of anoxic conditions that manipulates CH_4 and N_2O production and consumption. Maximum N_2O concentration in the soils is found at about Eh 200-250 mV (Letey et al., 1981; Yu et al., 2006). The anoxic soil can play a role for N_2O sink (Letey et al., 1981). High N_2O flux from soil is fluctuated by soil redox potential because of wet and dry cycle (Pathak, 1999).

Soil texture retaining water and air influences denitrification activity. N losses via denitrification in the intensively managed clay soil are high (van der Salm et al., 2007).

Temperature has an effect on denitrificaiton rate in the aspect of supporting microorganism growth. When increasing temperature, denitrification activity increases exponentially. Maximum, minimum, and optimum temperatures could activate denitrificaiton at 75º C, 2.7-10º C, and 50-70º C, respectively (Firestone, 1982).

The amount of N_2O emission whether high or low rate depends on the environmental factors that obstacle or support enzyme activity during denitrification. It should be considered the N_2O/N_2 emission ratio obviously that these bacterial processes may serve either as a source or as a sink. The factors that affect the proportion of N_2O and N_2 produced during denitrification are that 1) increasing NO_3^-, NO_2^-, O_2, and sulfide concentration can increase the ratio, 2) decreasing pH also can increase ratio and enhance the effect of NO_3^- (ŠImek and Cooper, 2002), 3) increasing carbon availability decreases ratio, 4) redox potential changes below 0 mV do not affect ratio, and 5) the occurrence or absence of N_2O reduction activity relative to preceding reduction can increase or decrease ratio (Firestone, 1982). It is confusing between the ability of soil to consume and to produce N_2O. For instance, N_2O consumption is positive in relation with dehydrogenase activity, but high NO_3^- content inhibits dehydrogenase activity (Włodarczyk et al., 2005). On the other hand, N_2O production increases nonlinearly with dehydrogenase activity (Włodarczyk et al., 2002). It is probably that N_2O sink in soil depends on the microbial population in nitrogen pathways. Environmental factors are the niche as controlling microbial activity.

2.4 Riparian ecosystem

Riparian ecosystem is ecozone between aquatic and terrestrial ecosystems, and providing various curial ecosystem services and functions (Naiman et al., 2005). Although the definition of riparian is different in various publications such as riparian ecosystem, riparian system, buffer zone, buffer stiff, riparian zone, and riparian wetland, such terms are synonym due to similar properties and their benefits in terms of ecological services and goods.

2.4.1 Riparian wetland in wetland definition

Wetlands are the places where environment condition and biotic system is influenced by water. They subject to permanent or periodic covered by shallow water or water table is closed to soil surface. The Ramsar Convention (2011) in Article 1.1 give wetland definition as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres". Moreover, the Article 2.1 mentions the potential incorporation of riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands. That term provides coherent area to protect wetland area.

Generally, wetland is classified into five types: 1) marine including coastal wetlands such as coastal lagoons, rocky shores, and coral reefs; 2) estuarine including deltas, tidal marshes, and mangrove swamps; lacustrine that is wetlands associated with lakes; riverine that is wetlands along rivers and streams; and palustrine such as marshes, swamps and bogs (Ramsar Convention Secretariat, 2011).

For Thailand, riparian wetland is categorized into five levels; type, system, subsystem, class, and subclass. It is note that crucial criteria of riparian wetland identification rely on salinity < 0.5 ppt, hydrological characteristics, geomorphologic setting, and land use following Table 2.5 (Chansaku, 2002).

Table 2.5 Thailand riparian wetland classification

Type	System	Subsystem	Class	Subclass
Fresh water (FR)	Riverine (FR)	River (FRR)	Perennial river (FRR1)	- Pool and riff (FRR1a) - Natural channel (FRR1b) - Artificial channel / Irrigation canal (FRR1bm) - Natural rapid (FRR1c) - Waterfall (FRR1d) - Hot spring /spring stream (FRR1e) - Underground stream / Cave stream / Sink stream (FRR1f)
			Seasonal river (FRR2)	- Pool and riff (FRR2a) - Natural channel (FRR2b) - Artificial channel / Irrigation canal (FRR2bm) - Natural rapid (FRR2c) - Waterfall (FRR2d) - Hot spring /spring stream (FRR2e) - Underground stream / Cave stream / Sink stream (FRR2f)
		River bank, Beach, Bar (FRB)		
		River floodplain (FRF)	Grass land / Grass swamp (FRF1)	- Grass land / Grass swamp (FRF1a) - Floodplain wet rice (FRF1am) Other agricultural types (FRF1bm)
			Natural Tree / Shrubs (FRF2)	- Seasonal flooded tree/shrubs (FRF2a) - Seasonal flooded / irrigated agricultural area (FRF2am)
			Seasonal flood plain lake >=80,000 sq. m. (FRF3)	
			Seasonal flood plain pond <80,000 sq. m. (FRF4)	
			Seasonal flooded swamp after levee (FRF5)	Natural field (FRF5a) Irrigated rice (FRF5am) Irrigated agriculture (FRF5bm)

Source: modified from Chansaku (2002)

2.4.2 Riparian wetland of Thailand

Riparian wetland in Thailand is identified as river subsystem (FRR) of 25,008 sites and covered area 2,765.51 sq km. Riparian wetlands of international importance in Thailand are 26 sites and found in different types and subtypes such as floodplain, permanent marshes, seasonal marshes, stream, river, international river, pool and pool in river, waterway, seasonal swamp forests, natural marsh, seasonal marshes with aquatic plants, waterfalls, and riverine flood plain. Regarding the wetlands of national importance located in river basin, national park, there are 28 sites (ONEP, 2002). Interestingly, almost riparian wetland sites are located either in conservation area or river and stream. In fact, the area along river and stream outside protection area can be counted as riparian wetland, but such riparian area is negligible in the protection area system in Thailand due to underrepresented when it is mixed by other land uses (Trisurat, 2007). It is difficult to delineate boundary. Buergin (2003) reported that riparian freshwater swamp forest which is subjected to inundated seasonal flooding in Songkhram River Basin, Northeastern Thailand have a small patch area and scattered along the river floodplain. Because of no single national park or wildlife sanctuary found to protect this ecosystem and used by local communities for non-timber product gartering and grazing, therefore, the remaining area is about 260 sq. km.

2.4.3 Structure of riparian zone

This study focuses on the riparian ecosystem as the adjacent of ecological zone of aquatic and terrestrial ecosystems closed to the river. The various forms of riparian zone can be found at the edge between terrestrial and aquatic ecosystems. It is represents a buffer zone where their structure can intercept and retain nutrients and sediment from shallow groundwater and runoff before draining to water system. In this study, riparian structure is range about 100 meter width that is served as buffer function of semi natural riparian system. These structures may have differences in size and arrangements (Figure 2.3). The arrangement within riparian zone may be composed of no buffer, buffered with agricultural areas with and without applied fertilizers, reforestation or forest buffer. In Thailand, it is rare for natural riparian ecosystem because of the influence of land use change for agriculture propose (Buergin, 2003).

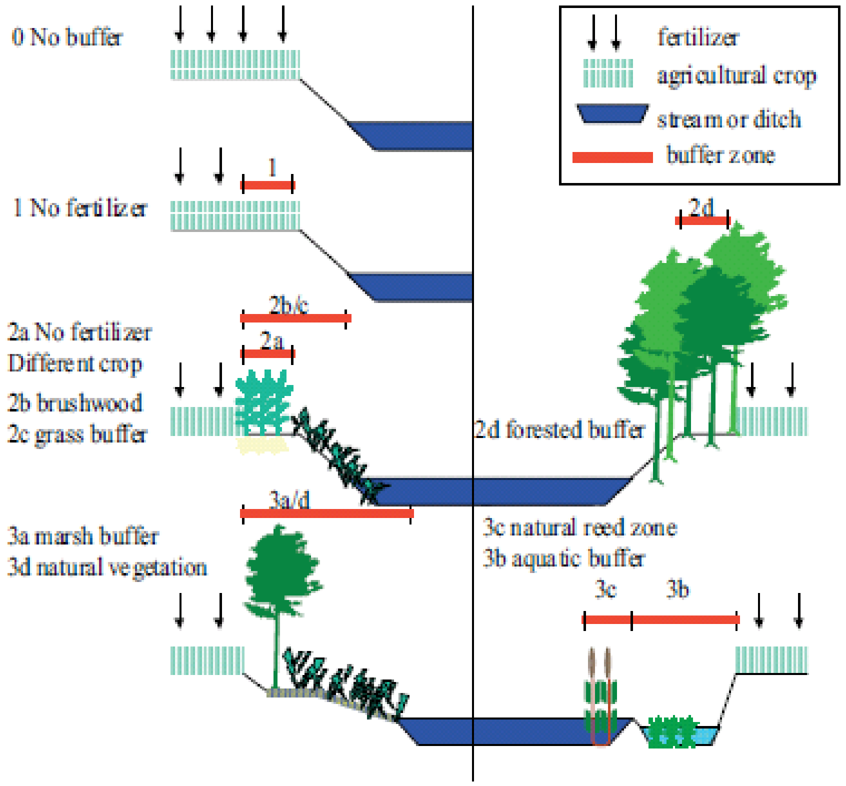


Figure 2.3 Riparian buffer zones present in size and arrangement (Hefting, 2003)

0 fertilizers with no buffer strips
1 narrow fertilizer-free buffer strips
2 fertilizer-free buffer strips with adapted vegetation
    a different agricultural crop
    b with natural brushwood
    c with grass
    d forested
3 fertilizer-free buffer strip with an adapted layout
    a marsh buffer zone with a reduced slope and natural herbaceous vegetation
    b aquatic buffer zone with submerged aquatic vegetation
    c natural reed zone
    d forested marsh buffer zone with a reduced slope

2.4.4 Riparian function and service

The biological and physical factors in riparian patches are connected by the flow of shallow groundwater, runoff, nutrients, and energy. One of prominent riparian services is detoxification that is filtered from water flow from agricultural area to stream or river and the water becomes clean with the high water quality.

The ability of riparian zone for filtering dissolved nutrient and sediment is due to their geographic position, geomorphic formation, hydrologic flow paths, and biological processes. It is the fact that riparian zone is located at the edge of terrestrial and aquatic ecosystems that all shallow subsurface and surface runoff have to flow pass through riparian zone before discharge to the stream.

The geomorphology of riparian zones is located at the lower gradients than uplands. When water and sediment are moved by the kinetic energy, riparian vegetation can catch the sediment to be deposited in riparian zone. Such process is served as ecological service to retain and intercept nutrient, chemical pollutants which come with particle sediment. The riparian function for nutrient removal and retention is well done when groundwater that carries dissolved nutrients flow through the root zone shallow. The degree of functional riparian to retain dissolved nutrients such as inorganic nitrogen, phosphate, and calcium is regulated by hydrological interaction (e.g. ground water, retention time, and amount of water), soil conditions, biotic properties (e.g. plant assimilation and microbial activities), amount of nutrient input into system, and different land uses. For example, riparian zone can protect water quality from nitrate contamination. Total nitrogen flow through riparian zone is measured from 67% to 89% of total loading. Riparian buffer zones designed for reduction nutrient loading may vary in different buffer width and arrangement (Table 2.6). The buffer zone width and plant cover are related to the effective of retention ability. The more buffer width is the more retention ability can be. Trees are better than herbs to absorb pollutant loading. The combination of wider buffer zone and mixed plant cover also enhances the reduction of sediment, nitrogen, and phosphorus loading in riparian zone.

Interestingly, the riparian zone is recognized more in semi-natural area or disturbed area than natural area in which riparian vegetation in natural forest is hardly found without impacts of anthropogenic activity. In this sense, the sediment and nutrient are natural process and low impact to stream.

Table 2.6 Effects of various riparian buffer zones on the reduction of inputs from surface runoff in the Chesapeake Bay catchments in the United States

Buffer Zone		**Reduction: 100 x (Input - Output)/Input**		
Width (m)	**Plant Cover**	**Sediment (percent)**	**Nitrogen (percent)**	**Phosphorus (percent)**
4.6[a]	Herbs	61.0	4.0	28.5
9.2[a]	Herbs	74.6	22.7	24.2
19.0[b]	Trees	89.8	74.3	70.0
23.6[a]	Herbs and Trees[c]	96.0	75.3	78.5
28.2[a]	Herbs and Trees[d]	97.4	80.1	77.2

[a] inputs: sediment 7.3 mg/L, nitrogen 14.1 mg/L, phosphorus 11.3 mg/L.
[b] inputs: sediment 6.5 mg/L, nitrogen 27.6 mg/L, phosphorus 5.0 mg/L.
[c] width comprises 4.6 m of herbs plus 19 m of trees.
[d] width comprises 9.2 m of herbs plus 19 m of trees.
Source: Naiman et al. (2005)

2.4.5 Nitrogen transformation in riparian zone

Riparian zone plays an important role as a sink of nitrogen and other nutrients involving mineralization, nitrification, denitrification, assimilation, retention or uptake by vegetation and microorganism, and storage in organic matter (Figure 2.4).

Denitrification is the most important biological processes to remove nitrate from riparian system. It reduces nitrate to N_2O and N_2. Denitrification removed N for 51% from catchments in the Northeastern USA (Van Breemen et al., 2002). The highest rate takes place at riparian zone closed to stream boundary in which the amounts of nitrate, soil moisture from exchange land and stream, and organic carbon are rich.

Assimilation by plant is also effective removal nitrate in riparian zone. It is uptaken in the top soil with a few centimeters depth. The non woody and woody uptake and accumulate nutrient in biomass forms. Riparian tree or forest is the best accumulator of nutrient because the rate of respiration is high, thus enhancing nutrient absorption of root system and photosynthesis. Also, some species have unique morphological and physiological adaptation for tolerating flooding and facilitating nutrient uptake under low oxygen condition. Assimilation rate at Rhode River, Maryland is 77 kg N ha^{-2} yr^{-1}. During log phase of plant growth, the rate of nutrient uptake is the primary mechanism of nitrate reduction (Correll, 1997).

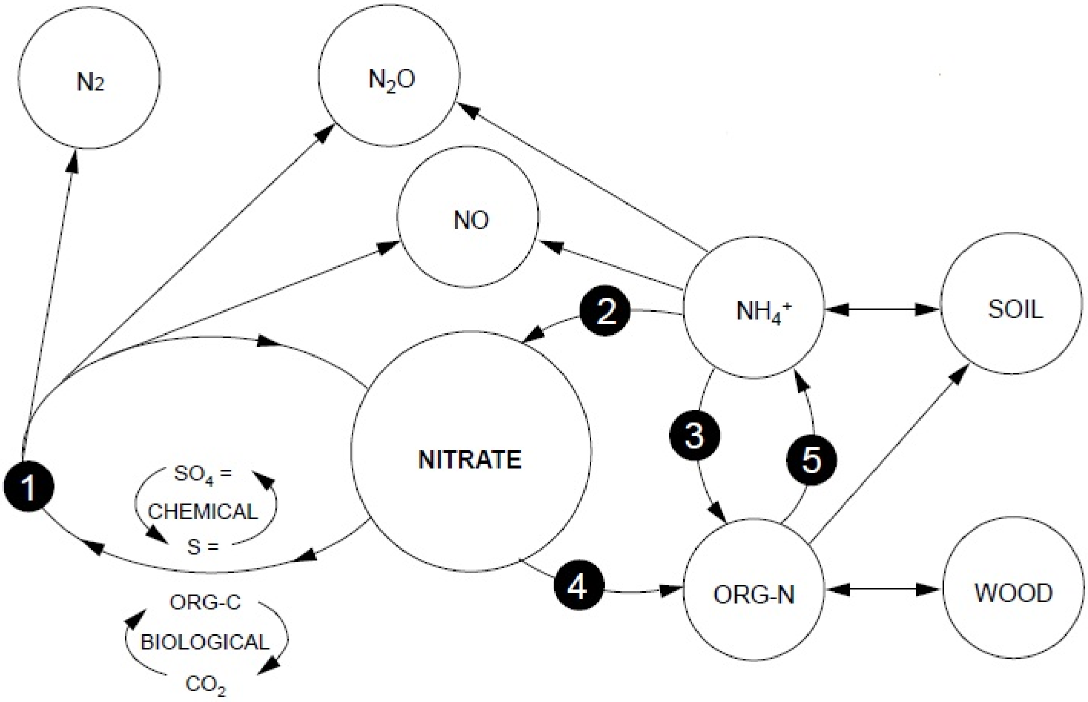


Figure 2.4 Functions and mechanisms involving nitrate removed from riparian zones (Naiman et al., 2005)

Remark;
1: Denitrification
2: Nitrification
3: Assimilation NH_4^+
4: Assimilation NO_3^-
5: Mineralization NH_4^+

Nitrification and mineralization are parallel processes that uptake and release ammonium from organic nitrogen. The high water content, temperature and soil respiration in riparian zone may increase nitrification and mineralization rates. The concurrent of nitrification and mineralization may also be high rate at the upper area and low rate at stream border due to the trend of lower oxygen status and high soil water content in pore space across lateral gradient. Then, the high rate of denitrification is dominating nitrate removing mechanism at the proximity to river edge. However, nitrification and denitrification occur simultaneously in soil.

Regarding the concept of an anaerobic balloon, oxygen can increase or decrease in soil pore due to water filled pore space and redox potential. Substrates used by microbial are allocated to the anaerobic and aerobic in soil.

2.4.6 Riparian zone induced high rate of N_2O emission

The ecological functions in riparian zone serve as filtering sediments and nutrients before leaching into water body, thus enhancing water quality. Due to high water content, anoxia, nitrate, and organic matter as substrates in denitrification, riparian zone is the hot spot of direct and indirect N_2O emission source (Hefting et al., 2003).

Cook et al. (2008) reported from several studies about N_2O emission from riparian zone that 1) annual N_2O emission rates from riparian wetlands are high uncertainty from 0 to > 100 kg ha^{-1}, 2) low N_2O emission may often find in applied low rate of nitrogen fertilizer, 3) permanently flooded wetlands have lower N_2O emissions than those exposed to fluctuating water tables, and 4) nitrate loading to riparian have significantly higher N_2O flux than adjacent wetlands with low inputs. In wetlands with low N_2O emissions, N_2O production is significantly higher within the zones of high nitrate reduction than outside that zone. Although total N gas production increases the proportion, N_2O as opposed to N_2 decreases.

N_2O emission rates in other wet environments (e.g. irrigated organic soils, tropical peat, lake sediments) are similar to those reported for wetlands because high N_2O emissions under a fluctuating water level regime appear due to oxygen becoming suboptimal for denitrification. Non-limiting carbon and nitrate under the fluctuating water level regime induce very high N_2O production. The highest peak of N_2O emission up to 80 mg N_2O m^{-2} d^{-1} can be found after flooding because of addition organic matter (Jacinthe et al., 2012).

It is concluded that nitrogen saturation from applied agricultural field, dynamic and gradient of high soil water content in lateral flow from upper area to stream edge, and high organic carbon from runoff and flooding are effective to enhance simultaneous nitrification and denitrification in riparian zone.

Although there are no the studies of N_2O emission from tropical riparian zone, tropical soil is the main source of N_2O emission (Davidson, 2009).

Tropical zone may be increased the turn over rate of nutrient cycling due to high temperature and humidity. The plant and soil respiration is high rate in tropical zone. In temperate zone, nutrient is stocked in soil; therefore, N transformation is easier than in tropical zone where nutrient and biomass are contained in plants. Conversely, the stable and high temperature in tropical zone may increase productivity, decomposition and nutrient turnover rate of soil more than in temperate forest (Vitousek and Sanford, 1986; Vitousek and Matson, 1988; Six et al., 2002), thus taking high opportunity N_2O emitted to atmosphere by high microbial activity. Table 2.7 shows how the ecological process and function in riparian zone do enhance N transformation.

Table 2.7 Condition, process and function enhancing N_2O formation by denitrification and nitrification in tropical riparian zone

Condition	**Process**	**Function enhance N_2O formation by denitrification and nitrification**
Land use change and agricultural activity	Applied fertilizer and nitrate leaching	High nitrogen loading
Stream flow exchange , runoff, erosion, and flooding	Wood debris, sediment deposit, dynamic high water content	High organic carbon Anaerobic condition and reduction state at the same time across lateral gradient
Climatic tropical zone	Stable/ high temperature and humidity	Speed up decomposition and high nutrient turnover all year round

2.5 Spatial and temporal of N_2O variability

The variability of nutrient concentration and physical factors found in riparian zone is a consequence of spatial heterogeneity due to the processes of disturbance such as flooding and drying, and the interaction of geomorphology and hydrology at longitudinal and lateral transfer (Fisher and Welter, 2005).

N_2O shows very high uncertainty. Annual N_2O emission rates from riparian wetlands range from 0 to > 100 kg ha^{-1} (Cooke et al., 2008). The spatial and temporal variability of nitrogen transformation and environmental condition across riparian zones makes it difficult to determine the accuracy rate of denitrification, nitrification and N_2O formation and emission and to upscale to wider areas. For example, a spatial difference of N_2O flux is ranged from 15 to 350% for 3-8 replicates in natural system. It is found that spatial and temporal N_2O flux in which seasonal soil moisture, hydrologic gradient and soil micro sites in the soil column are dynamic across riparian zone. N_2O uncertainty is explained by the concept of landscape ecology that ecosystem process is heterogeneous. Heterogeneity is a result of interactions among different abiotic factors (e.g. climate, topography, and substrates), biotic assemblage, disturbance events, and human activity in patches of landscape mosaics. Ecosystem process can be measured as the point processes and lateral transfers. A point process is the rates of ecosystem function at a site-specific location such as net primary productivity, net ecosystem product, denitrification or nitrogen (Figure 2.5 a) while lateral transfers are supposed to be a small relative to the measured response such as flow of nitrogen or phosphorus from land to water (Figure 2.5 b).

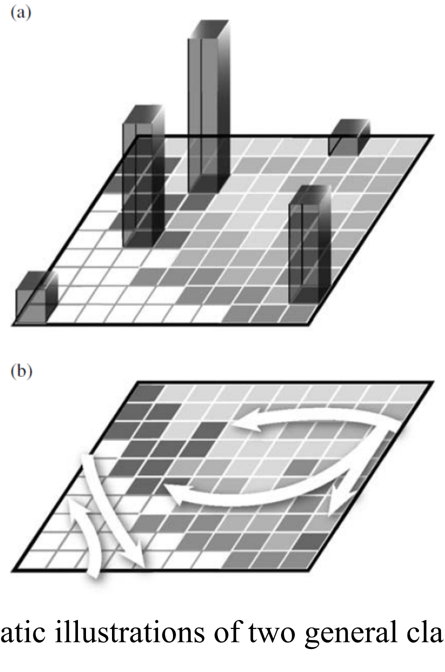


Figure 2.5 Schematic illustrations of two general classes of ecosystem processes: (a) point processes and (b) lateral transfers (Turner and Chapin, 2005)

2.5.1 The importance of spatial heterogeneity

There are three important situations when spatial heterogeneity is important for ecological study (Turner and Chapin, 2005).

1.) Understanding the accuracy of average rate of ecological process

Spatial heterogeneity is used to explain the ecosystem processes because the parameters (e.g. nitrification and denitrification) as a result of ecological function are a nonlinear across landscape. For example, the average rate of N_2O emission process may be high standard deviation if it is observed in different moisture regime and land use. Therefore, the estimation of average flux from this landscape would be inaccurate. Sampling method of different spatial variation (e.g. soil condition and land use) may reduce the uncertainty.

2.) Understanding the responding variables by scale observation

The significantly different responded variables (e.g. N_2O flux and denitrification) can occur at each scale observation. Both space and time of observation affect the respond variable of direct interest. Changing in N_2O emissions is observed by the sampling scale due to micro sites as sources of N_2O in this soil. Denitrification variation is at the <0.1 m scale (Parkin et al., 1987). To reduce uncertainty, the sampling scale of N_2O emission was reduced to 1 to 6 m (Parkin et al., 1987; Clemens et al., 1999; Röver et al., 1999). Small temporal variations (e.g. weekly and monthly) assume at stable environmental conditions and have homogeneous local variation. Usually, the fine scale needs the precise of measurement. So, determine time period for measurement varies depending on interesting target.

3.) Understanding spatial pattern and lateral transfer in response to dependent variables

Spatial composition and configuration in landscape become one of the independent variables in ecological study. The explanation of the flux of nutrient from upland to aquatic ecosystem is outstanding sample of the relationship of the effect of spatial pattern and lateral transfer. For example, the patch size and arrangement of crop fields and forested riparian affect nitrogen and phosphorus loading to stream. So, the sequence of land cover type is used to design as buffer strip to intercept sediment and nutrient in riparian ecosystem (Figure 2.3). The edges of field and riparian zones and/or riparian zones adjacent with stream edge are often expected high spatial and temporal N_2O flux (DeSimone et al., 2010). Figure 2.6 shows that the relation of oxygen and available nitrate to nitrification and denitrification varies on distance along hyporheic flow path. At the upper zone presented of organic nitrogen and O_2, nitrification and NO_3^- production will be high rates. When oxygen has been partially or totally consumed, thus generating anaerobic condition, then denitrifying bacteria community is dominated and nitrate is reduced. (Naiman et al., 2005).

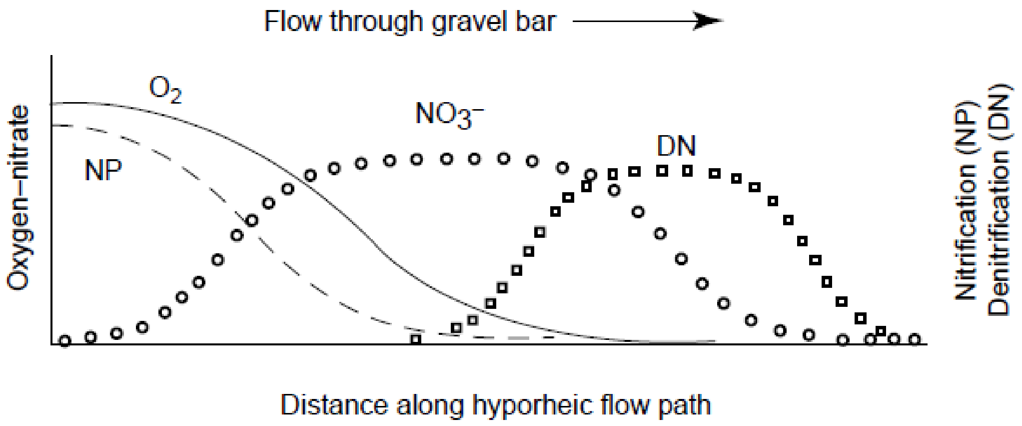


Figure 2.6 The variation of oxygen (O_2), nitrate (NO_3^-), nitrification (NP), and denitrification (DN) along a hyporheic flow path through a gravel bar (Naiman et al., 2005)

CHAPTER III

METHODOLOGY

3.1 Study site

The Nan River is one of the important national-level wetlands of Thailand. It is classified as riverine system with permanent river (ONEP, 2002). The criteria were considered to select specific study site on the basis of the concept of riparian wetland landforms, hydrologic, and soil characteristics; 1) surrounded by upland and toward drainage direction to river; 2) closed to river where riparian ecosystem is affected by lateral transfer; 3) located in floodplains in which there are floods and fluctuated water levels; and 4) settled in alluvial soil in which riparian zone is hydric soil and substrates (Tiner, 1999). There is no occurrence of natural hydrophytes because of land use disturbed by local people to riparian ecosystem. This indicator for delineating riparian ecosystem is skipped.

Therefore, the study sites were classified as river floodplain (FRF) with seasonal flooded tree (FRF2a) and seasonal flooded / irrigated agricultural area (FRF2am). Three tropical riparian study sites were chosen with their location in parallel to the Nan River in Nan province, Northern Thailand. Specifically, they were located in the Tan Chum sub-district; 1st site (18º37’13.04”N, 100º45’44.20”E), the Klang Wiang sub-district; 2nd site (18º35’04.89”N, 100º45’46.79”E), and the San sub-district; 3rd site (18º33’27.91”N, 100º45’46.29”E) (Figure 3.1).

The study sites are classified as tropical climate and the study area has an average annual rainfall of 1,090 mm in the wet season (May-Oct.) and 177 mm in the dry season (Nov.-Apr.). The average annual minimum and maximum temperature during 1951-2009 were 21.8°C and 34.6°C in the wet season and 13.4°C and 36.5°C in the dry season, respectively. The average shallow ground water depths are 0.05 to -5.37 m in the wet season and -4.42 to -7.35 m in the dry season (AEDE, 2010) (Figure 3.2).

The land use patterns of Wiang Sa district are dominated by maize (31,029 ha), rice (3,888 ha), and orchard and reforestation (5,464 ha) (DOAE, 2008). All three study sites included both maize and reforestation areas are located on alluvial floodplain soils (altitude, 200 m MSL., 0-3% slope), subject to annual flooding for 2-5 days.

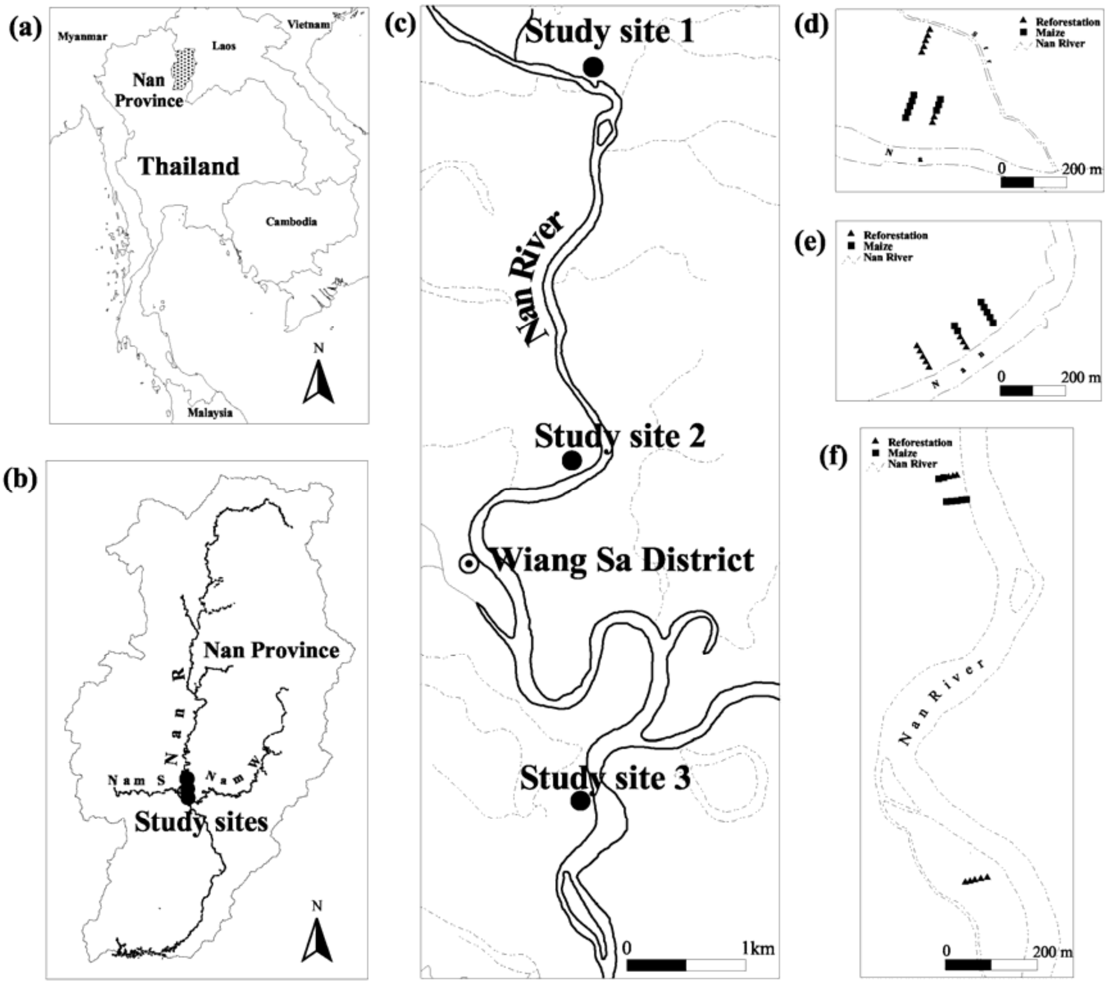


Figure 3.1 (a) Maps depicting the general location of the study sites within Thailand, (b) the Nan River Basin, (c) overall three locations of the riparian N_2O monitoring sites, (d, e, and f) the riparian N_2O monitoring 1st, 2nd, and 3rd site, respectively.

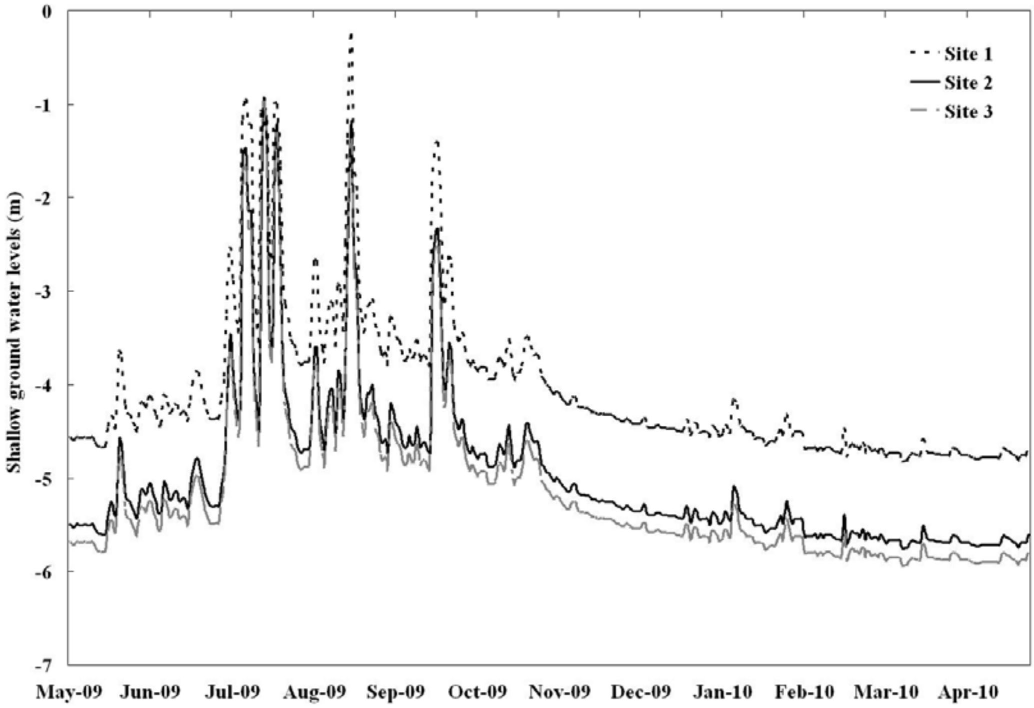


Figure 3.2 Average daily shallow ground water levels (m) of three experimental riparian study sites (AEDE, 2010).

3.2 Experimental design

3.2.1 Transect types

The experimental riparian study sites were characterized as reforestation areas, composed solely of N-fixing trees (*Samanea saman* (Jacq.) Merr), maize (*Zea mays* L.), or a mixture of the two (*i.e.*, mixed land use with reforestation close to the river and maize planted further upslope) transect (Figure 3.3 and 3.4 a, b, and c). Regarding the riparian structure and arrangement (Hefting, 2003), reforestation, maize, and mixture transect of this study are fertilizer-free buffer strip with forested (2d), crop applied fertilizers with no buffer strip (0), and fertilizer-free buffer strip with forested coupled with crop applied fertilizers with no buffer strips (2d and 0), respectively. The experimental plots were about 100 m in length at 90° to the river and approximately 50 m in width (0.5 ha).

S. saman (Jacq.) Merr is the common tree grown in the riparian forestation along Nan River due to its capability to adapt to saturated soil and seasonal flooding. Local people have been cultivated *S. saman* (Jacq.) Merr for 50 years. In the *S. saman* (Jacq.) Merr forestation blocks, the tree spacing ranges from 8 to12 m, and the average stand age is 15 years. The average and standard deviation of tree height, diameter at breast height (DBH), and basal area are 20±5 m, 46±16 cm, and 11.7±3 m^2 ha^{-1}, respectively (Appendix 1). The forest are utilised for harvesting lac served by *Laccifer lacca* Kerr. and for timber and non timber product.

In the crop blocks, maize has been double cropped in May and September for 30 years. Planting occurs on ridges of 75 cm apart (25 cm plant spacing), and harvesting takes place around 95-120 days after planting in combination with an intensive inorganic nitrogen fertilizer application. Inorganic N fertilizer formula, either 16-20-0, 15-15-15, or 46-0-0 is applied at the rate of 175 kg N ha^{-1} twice: first, during maize sowing and, second, either 15-30 days after seeding or after weed elimination. Thirty days after an initial ploughing in April and August, farmers undertaker a second ploughing for maize sowing.

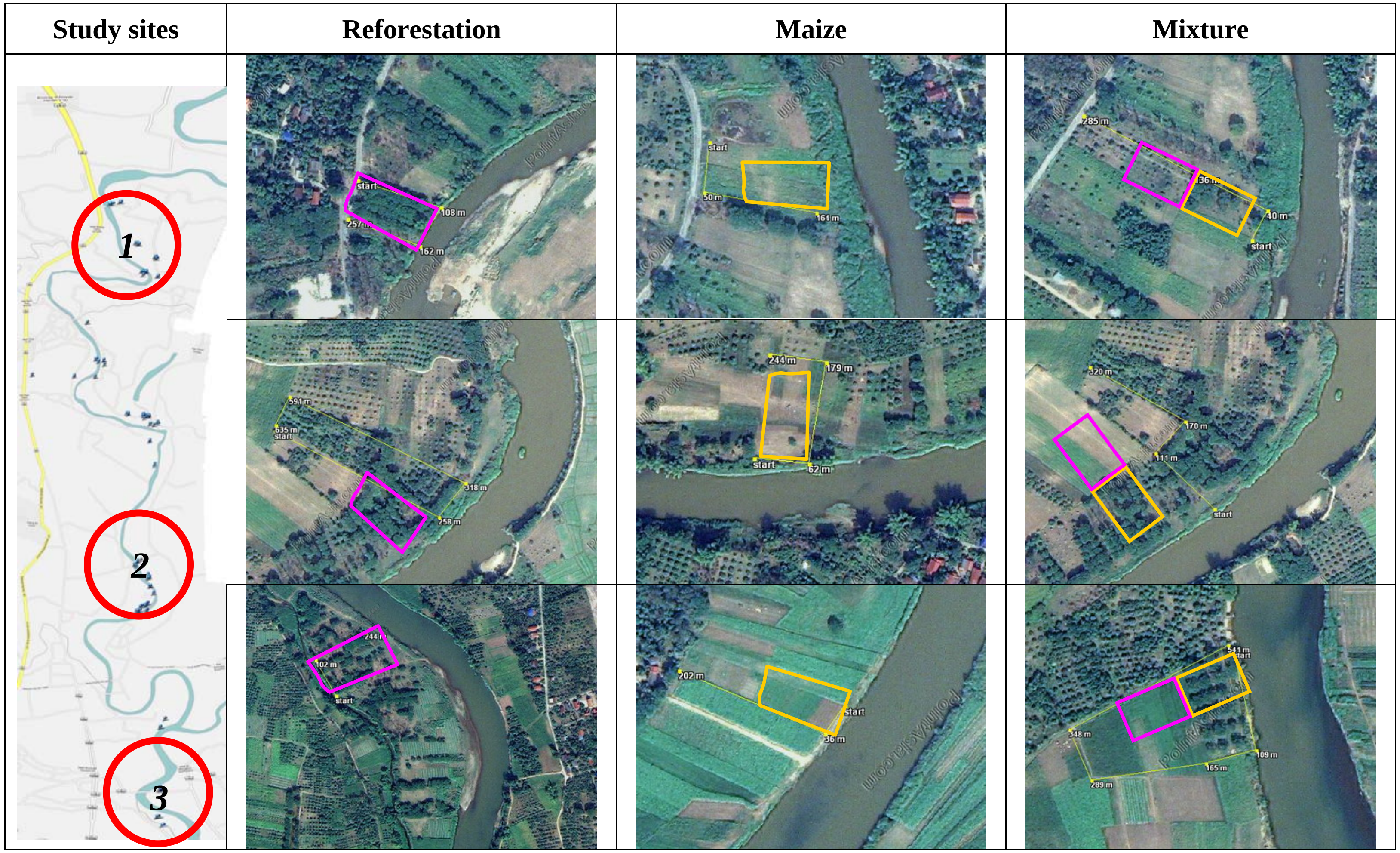


Figure 3.3 Satellite images of study sites. Pink and yellow colour boxes are reforestation and maize area, respectively.

a) Reforestation transect

b) Maize transect

c) Mixture transect

Figure 3.4 Different land uses in riparian ecosystem study sites

3.2.2 Sampling location

To analyze N_2O emission and soil-environmental parameters with respected to the point and lateral processes, along about 100 m transect downstream, five sampling locations were taken at 18.5 m intervals with random horizontal locations. N_2O flux and soil-environmental parameters were measured at each spot samples (reforestation *n*=23, maize field *n*=22) on monthly basis from May 2009 to April 2010. The classification of five sampling locations named as per the proximity to the Nan River, called field boundary; FB *(n* = 9), adjacent to field boundary-interval zone; AFI *(n* = 9), interval zone; IZ *(n* = 9), adjacent to interval zone-river side; AIR *(n* = 9) and river side; RS *(n* = 9) (Table 3.1).

Table 3.1 Experimental designs to analyze N_2O emission and soil-environmental parameters in the tropical riparian zone with respect with the point process (the results were means and standard error of the mean categorized by land use types) and the lateral process (the results were means and standard error of the mean categorized by the proximity of sampling location to river and land use configuration).

Transect type		Sampling location proximate to the Nan River				
		1. RS	2. AIR	3. IZ	4. AFI	5. FB
Reforestation Transects (n=3)	Nan River	Reforestation (Aa)	Reforestation (Ba)	Reforestation (Ca)	Reforestation (Da)	Reforestation (Ea)
Maize Transects (n=3)		Maize (Ab)	Maize (Bb)	Maize (Cb)	Maize (Db)	Maize (Eb)
Mixture Transects (n=3)		Reforestation (Ac)	Reforestation (Bc)	Reforestation/ Maize (Cc)	Maize (Dc)	Maize (Ec)

The experimental design to analyze N_2O emission and soil-environmental parameters respect to the point process and lateral transfer alike in that both are the same sampling location. The former was created for observing as the point processes of the average rate of N_2O emission from different land uses and seasonal variation, while the latter was utilized for determining; 1) the effect of lateral transfer on N_2O flux variability and soil properties across tropical riparian zone due to the spatial proximity of sampling location to river and spatial arrangement within each transect types (capital letters in Table 3.1), and 2) the variation of N_2O flux variability and soil properties due to sampling locations at upper zone toward to rive edge among transect types (small letter in Table 3.1).

It was remarked that reforestation transect, agricultural area with maize transect was established to study spatial proximity but no spatial arrangement due to homogeneous land use type across from upper area to river edge, while mixture transect was designed to study both spatial proximity and spatial arrangement of a mixture of two land use types in which maize patch in further upslope is connected with reforestation patch close to river. Therefore, reforestation and maize was a control treatment.

3.3 N_2O emission measurement

3.3.1 N_2O flux collection

Soil N_2O emissions were measured by using non-flow through non-steady-state (NFT-NSS) chambers adapted from Rochette and Bertrand (2008). The acrylic plastic chambers (40 cm × 40 cm × 15 cm) were equipped with a sampling port and covered with foam thermo-foil to maintain ambient pressure and temperature (Figure 3.5). The metal base frames of the chambers were inserted into the soil to a depth of 15 cm. They were permanently installed in the reforestation plots, but removed temporarily from the maize plots during ploughing, and replaced after plowing at least 7 days prior to gas flux measurements. Gas samples were taken at 0, 10, 20, and 30 min after sealing the chamber into the frame base from 9:30 am to 11:00 pm. Gas samples from the chambers (10 ml) were placed in pre-evacuated vials and hermetically sealed. Temperatures of the ambient air in chamber, and soil (0-5 cm depth) were recorded at each chamber sampling alongside with relative humidity (Figure 3.6 a).

3.3.2 N_2O flux determination

Gas samples (800 µl) were analysed for N_2O by using an Agilent 6890N gas chromatograph equipped with a 15 m × 0.53 mm PLOT GS-Q column. The analysis conditions included: column temperature 40°C; injector temperature 50°C; pulsed split mode, at ratio 5:1; µECD detector temperature 300°C; N_2 carrier gas 5.5 ml min^{-1}; standard N_2O gas concentration 1 mg l^{-1}. The relative standard deviation (RSD) for repeat injections and minimum detectable flux were <2% and 3.87 µg N_2O N m^{-2} h^{-1}, respectively. N_2O gas fluxes were calculated via the regression model (Watanabe et al., 2000):

$$F_{N_2O} = \rho \times (V/A) \times (\mathrm{d}G/\mathrm{d}t), \qquad (1)$$

where F_{N_2O} (mg N m^{-2} h^{-1}) is the N_2O flux rate, ρ (mg N m^{-3}) is the density of N_2O at the time of sampling corrected for pressure and temperature inside the chamber, V is chamber volume (m^3), A is basal area (m^2) and $\mathrm{d}G/\mathrm{d}t$ is the change of ρ per unit time (mg N_2O N m^{-3} h^{-1}). $\mathrm{d}G/\mathrm{d}t$ is not included in the flux equation if the R^2 value is < 0.9.

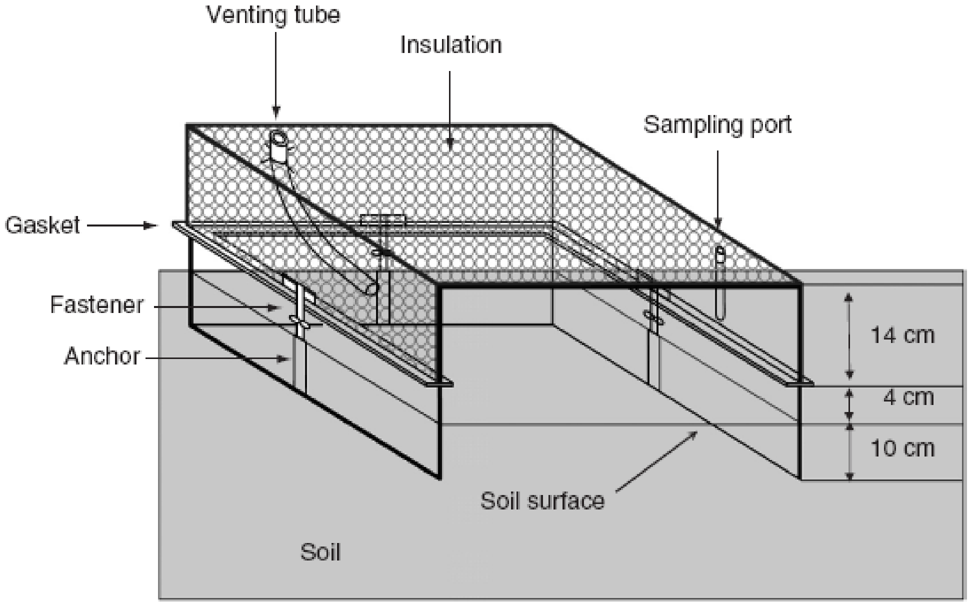


Figure 3.5 Non-flow through non-steady-state (NFT-NSS) chamber (Rochette and Eriksen-Hamel, 2008).

3.4 Soil sample collection and preparation

Within each experimental plot, 3 replicate batches of 5 intact soil cores (5 cm high and 5.45 cm diameter) (Figure 3.6 b) and 5 soil samples (0-5 cm depth) (Figure 3.6 c) were collected and stored at 4ºC for further analysis. It is noted that N_2O subsurface diffusion beneath soil at 0-15 cm depth is trapped in micro pore site, therefore the soil sample collected at 5 cm depth is representative (DeSimone et al., 2010). Within 4 hours of collection, the intact soil cores were weighed and used to determine the N_2O production rate via denitrification in the laboratory (see below). The undisturbed soil cores were used to determine microbial biomass carbon, available NH_4^+, NO_3^-, and dissolved organic carbon. Briefly, soluble soil were extracted from 5 g of field-moist soil samples with 25 ml 0.5 M K_2SO_4 at 250 rpm for 1 h, then, centrifuged at 4,000 rpm at 4ºC, for 12 min and filtered by 42 µm pore size, finally preserved at -20ºC to await analysis (Jones and Willett, 2006). The remaining soil samples were air-dried and sieved (<2 mm) for soil pH in H_2O and textural analysis and further sieved (<500 µm) prior to total C and N analysis. Gravimetric soil water content, bulk density, porosity, and water filled pore space were determined on intact soil cores after drying at 105°C (72 h) or until stable weight.

a) Collected N_2O flux by closed chamber method

b) Collected intact soil core by soil core

c) Collected soil sample by soil auger

Figure 3.6 N_2O flux, intact soil core, and soil sample collection methods

3.5 N_2O production from denitrification

N_2O production from denitrification was determined in the laboratory using the acetylene block method (Drury et al., 2008). Intact soil cores were placed in a gas-tight box (850 cm^3), evacuated for 3 min, and flushed with N_2 gas for 3 min to induce anaerobic conditions. The headspace was then replaced with N_2 gas containing acetylene (5% v/v), and the soil was incubated at 25ºC to match condition in the field (Ryden et al., 1987; Yoshinari et al., 1997). Subsequently, a 12 ml headspace gas sample was collected after 1, 2, 4, and 6 h, and injected into 10 ml vacuum glass vials. Gas samples were analysed as previously described. Control treatments were also undertaken but in the absence of acetylene. Denitrification rates were calculated as the rate of N_2O density over time in the headspace using a linear model ($R^2 > 0.9$).

Firstly, the calculation of the volume of N_2O gas at any time of observation (VN_2O_t) is defined by

$$V_{N_2O_t} = \frac{C_t[Vh+(V_{water}\alpha)]}{CF_n} \times \frac{1\ \mathrm{L}}{1000\ \mathrm{mL}}, \qquad (2)$$

where $V_{N_2O_t}$ (µL) is the volume of N_2O emitted from soil at time *t*, C_t (µL N_2O L^{-1}) is the N_2O gas concentration in the gas phase at time *t*, Vh (mL L^{-1}) is the headspace volume, V_{water} (mL L^{-1}) is the water volume in the soil core during incubation, α (mL N_2O mL^{-1} water) is the Bunsen absorption coefficient, and CF_n is the dimensionless correction factor.

Secondly, the calculation of the concentration of N_2O-N at any time of observation ($\mathrm{N_2O\ N_t}$) is defined as:

$$\mathrm{N_2O\ N_t} = \frac{V_{N_2O_t} \times P \times (28.0134\ \mathrm{g\ N_2O\ N\ mol^{-1}})}{\mathrm{R \times T \times M_s}}, \qquad (3)$$

where $\mathrm{N_2O\ N_t}$ (µg N_2O-N g^{-1}) is the concentration of N_2O-N at time *t*, $V_{N_2O_t}$ (µL) is the volume of N_2O in the incubating airtight box, P is the pressure in kPa, R is the universal gas constant (8.31451 L kPa mol^{-1} K^{-1}), T is temperature in K, and M_s is the oven-dry mass of soil (g). N_2O:N_2O+N_2 ratios were estimated by comparing the amount of N_2O production from intact soil cores in the presence or absence of C_2H_2 (Vinther, 1984). This parameter is useful to determine N_2O emission as a consequence of whether nitrification or denitrification. Therefore, proportion of N_2O formation due to nitrification, denitrification and reduction to N_2 was based on a water-filled pore space (WFPS) of approximately 35-60%, 60-70% (Bateman and Baggs, 2005) and >70% (Veldkamp et al., 1998), respectively.

3.6 Net nitrogen mineralisation and net nitrification

Net nitrogen mineralisation and net nitrification rates were measured in the laboratory using soil collected every other month from all the experimental plots from May 2009 to April 2010. They were assessed using the 28-day aerobic incubation (25°C) following the method of Robertson et al. (1999) with NH_4^+ and NO_3^- extracted in 0.5 M K_2SO_4 and assayed as described below.

3.7 Soil characterisation

Microbial biomass carbon was determined by the $CHCl_3$ fumigation-extraction procedure of Margesin et al. (2005). Briefly, 5 g of field-moist soil was fumigated for 24 h, extracted with 0.5 M K_2SO_4, and dissolved organic carbon (DOC) levels in the extracts determined by dry combustion (Analytic Jena, model 3100 C/N). Microbial biomass carbon was calculated as the difference in DOC between fumigated and non-fumigated soil using an extraction efficiency correction factor of 0.38. Soil pH was determined on <2 mm air-dried soil in a 1:2 (w/v) distilled water extract (Hendershot et al., 1993). NO_3^- and NH_4^+ in the K_2SO_4 extracts were determined colorimetrically according to the vanadate procedure of Miranda et al. (2001) and the salicylate-nitroprusside-hypochlorite procedure of Mulvaney (1996), respectively, and DOC was determined by combustion (Analytic Jena, model 3100 C/N). Total soil C and N in the <500 µm fraction of the air-dried soils were determined with a TruSpec® CN analyser (Leco Corp, St Joseph, MI). Soil texture was determined on the <2 mm air dried fraction of soil by the hydrometer method of Sheldrick and Wang (1993). Bulk density (D_b) and Water filled Pore Space (WFPS) were determined according to Blake (1965) and Schindlbacher et al. (2004), respectively.

3.8 Biomass and nitrogen fixation

To estimate emission factor and explain nitrogen turnover rate, the quantity of total nitrogen input to riparian ecosystem is necessary. Then, biomass of reforestation and maize and rates of N-fixation rate were determined.

Litter fall was also monitored by placing 3 replicate litter traps (1 m^2, 0.45 m deep) in each reforestation plot to collect leaves, flowers, fruits, bark, and twigs. Traps were emptied monthly in the dry season.

The yield of maize biomass, including surface litter, cobs, and stem/leaves in 12 m^2 plots at each field site, was determined in the dry season by harvesting The samples of litter fall and crop residual were dried at 80°C for 48 h.

The C and N contents in biomass dry weight were estimated by multiplying the biomass values by 0.422 (Jans et al., 2010) and 0.015 (Bationo et al., 2007), respectively (Appendix 2).

At the reforestation plot, all the individual trees were measured at a breast height (DBH) of 1.30 m. Basal area (m^2) was calculated by $0.00007854 \times \mathrm{DBH}^2$. Biomass of individual trees was estimated using an allometric equation as follows:

$$M = a(\mathrm{DBH}^2)^b \qquad (4)$$

where, M is the subordinate variable describing the biomass for different tree parts. a and b coefficients for the above-ground biomass, root, stem, branch, and leaf are 0.4382 and 0.989, 0.03436 and 0.977, 0.1009 and 1.267, 0.001117 and 1.612, and 0.006845 and 1.098, respectively (Hiratsuka et al., 2010). N fixation rates of *S. saman* was determined by %N derived from atmospheric N (*%Ndfa*) multiplied by the N content of leaf and root biomass. *%Ndfa* was calculated according to Amarger (1979) as follows:

$$\%Ndfa = \frac{\delta^{15}Nr - \delta^{15}Nf}{\delta^{15}Nr - \delta^{15}Na} \times 100 \quad (5)$$

where, ^{15}N abundance % ($\delta\ ^{15}Nf$) of *Samanea saman* (Jacq.) Merr is 6 %, neighboring reference non-fixation plants ($\delta\ ^{15}Nr$) of *Tridax procumbens* is 3.1 % (Yoneyama et al., 1993), and the value for legume grown with air as their only source of N ($\delta^{15}Na$) is -1.3 (Domenach et al., 1989) (Appendix 3).

3.9 Direct N_2O emission factor (EF)

N_2O direct emission factors were determined by the IPCC method for direct emissions, EF (IPCC, 2006). The EF was calculated by percentage of N lost as direct N_2O emission divided by total N input summarized from applied chemical fertilizer, crop residual, for maize plot and N fixation for reforestation.

3.10 Statistical analysis

Significant differences in mean N_2O emissions among the two land use types, across seasonal variations, and their interaction were examined by *F*-test (two-way ANOVA). Significant differences of the sampling locations proximity to river within and among transect and seasonal variation on mean N_2O emissions and soil properties were examined by *F*-test (one-way ANOVA) and Duncan post hoc test to determine homogeneous subsets.

The relationship among N_2O flux, denitrification, nitrification, and environmental parameters were explained by Spearman's rho correlation coefficient, Redundant Analysis (RA), a Monte Carlo Test, and an ordination diagram using CANOCO (ver. 4.5).

Non-normal distributed data was transformed by the log transformation to achieve the normality and tested homogeneity of variance before statistical analysis.

CHAPTER IV

SEASONAL VARIATION OF N_2O EMISSIONS IN DIFFERENT LAND USE TYPES AND THEIR CONTROLLING FACTORS IN A TROPICAL RIPARIAN ECOSYSTEM, NORTHERN THAILAND

Abstract

An important ecological service provided by tropical riparian ecosystems is the mitigation of nitrogen pollution from surrounding agricultural areas. However, a negative impact of this nutrient remediation may be that the ecozone also functions as a major emitter of N_2O. It is hypothesize that the high inorganic nitrogen, organic carbon, and soil water content in tropical riparian ecosystem enhances N_2O production through rapid nitrification and denitrification processes**.** This study was aimed to quantify the variability of seasonal N_2O emissions in such an ecosystem comparing between a leguminous reforestation, *Samanea saman* (Jacq.) Merr, and applied nitrogen fertilizer in conventional agriculture with maize, *Zea mays* L, and to identify the major drivers controlling these emissions. At the results, using *in situ* closed chambers, the annual average emissions of N_2O from the reforestation area (3.3 kg N_2O-N ha^{-1} y^{-1}) was significantly higher than agricultural areas with maize (2.2 kg N_2O-N ha^{-1} y^{-1}) ($P<0.05$). The temporal variation results indicated that the rate of N_2O flux in the wet season was also significantly higher than in the dry season ($P<0.05$). The variations of N_2O flux were strongly correlated with water filled pore space (WFPS), denitrification, and microbial biomass carbon, but not with nitrification. This study indicates that when inorganic nitrogen and soil organic carbon are sufficient, WFPS plays an important role in controlling N_2O emissions contributed by denitrification. Comparatively, the annual N_2O emissions from the reforestation area in the tropical riparian zone were similar to that reported for temperate riparian zones and other ecosystems. Although the annual N_2O emission from the agricultural area with maize is comparable to other riparian ecosystems, it is higher than those of other N_2O fluxes from terrestrial zones. It is conclude that tropical riparian zones surrounding agricultural land do not represent a major hotspot of N_2O emissions and that this does not diminish positive benefits they provide in relation to other aspects of ecosystem service provision.

Keywords: Riparian ecosystem; N_2O emission; Land use types; Seasonal variation; Controlling factors.

4.1 Introduction

Nitrous oxide (N_2O) concentrations of atmospheric have been raising during industrial revolution and contribution 6% of total anthropogenic radiative forcing (Davidson, 2009). Microbial production in agricultural soils represents the dominant source of this N_2O emission which has progressively increased as the use of nitrogen (N) fertilizers increased globally. At present, N_2O emissions from agro-ecosystems represent approximately 60% of all anthropogenically derived N_2O emissions (Smith et al., 2007). Although N_2O emissions have been intensively measured and modelled in high input and large scale agricultural production systems, significant variation surrounds emissions from less intensive systems, particularly in tropical environments (Lokupitiya and Paustian, 2006).

Riparian system is identified as ecological zone between aquatic and terrestrial ecosystems and serving various ecosystem services and functions (Naiman et al., 2005). For example, riparian zones play an important role as a sink for particulate and soluble C, nutrients, and pathogens arriving via river flooding and runoff or leaching from neighbouring upslope areas (O'Donnell and Jones, 2006). Many of the nutrients (*e.g.*, PO_4^{3-}, NH_4^+, NO_3^-) become sequestered by the plant biomass or soil microbial community preventing a loss in water quality (i.e. reduced risk of eutrophication, maintenance of light penetration into the water column, minimal changes in benthic community functioning and composition (Kuusemets et al., 2001; Gibson and Meyer, 2007). However, the high water table and the potential for reducing favourable conditions that prevailed in riparian soils, the significant losses of N could occur via denitrification, making riparian zones potential hotspots for N_2O emission (Groffman et al., 2000; Vellidis et al., 2003; Verhoeven et al., 2006). Although the role of riparian zones in biodiversity and water quality are well understood, great uncertainty still involves their quantitative role in greenhouse gas emissions at the landscape scale (Gundersen et al., 2010).

The major environmental factors controlling nitrification and denitrification in riparian soils include the water table level, O_2 concentration, the quality and quantity of labile C, and the availability of inorganic N (Firestone, 1982). In riparian areas, fluctuating water tables often lead to the formation of discrete aerobic and anaerobic patches in the soil, favouring simultaneous nitrification and denitrification to N_2O (Bateman and Baggs, 2005). The formation of aerenchyma by plant roots increases this spatial heterogeneity and leads to the O_2 enrichment of the rhizosphere soil. In contrast, if the water table reaches the soil surface and the air filled pore space decreases to <10% of the soil volume, then N_2 may be produced rather than N_2O (Veldkamp et al., 1998). N_2O production may increase following the addition of organic C (e.g. as leaf litter, root exudates, and root/microbial turnover), depending on its quality, and organic matter inputs may also induce N immobilisation, thereby reducing nitrification and denitrification (Garcia and Tiedje, 1982; Choi et al., 2006).

Different land use types may induce different rates of N_2O emission. Comparatively, riparian wetland plant strip has a higher N_2O emission rate than that without plant cover (Hernandez and Mitsch, 2006). As another example, cultivated and uncultivated wetlands emit N_2O at significantly different rates over the same period (Bedard-Haughn et al., 2006). Also, changing peat lands into cultivated uplands and paddy fields increases the N_2O emission rate because of the changing water table, soil moisture contents, and addition of ammonium fertilizer or C from rice straw (Hadi et al., 2000).

Seasonal variation in plant production and temperature alongside seasonal fluctuations in water table depth likely lead to significant temporal variation in N_2O fluxes in riparian zones. For example, dry warm seasons can stimulate organic matter breakdown and NO_3^- production, and the start of the subsequent wet season may induce the loss of N_2O when water logging occurs (Dalal et al., 2003). Furthermore, constant nutrient replenishment may occur in the wet season due to fertilizer runoff and leaching from immediately adjacent agricultural land (Lowrance et al., 1984; Entry and Emmingham, 1996). Greenhouse gas emissions from these neighbouring agricultural areas may also be indirectly affected by riparian areas due to the influence of the latter on hydrological flow and consequently on water table depth (Naiman et al., 2005).

Because of rapid organic matter mineralisation and increasing fertilizer N use in tropical agricultural regions, these soils represent a major global source of N_2O (Reay et al., 2007). Relative to temperate agro-ecosystems; however, there are few studies of N_2O emissions from tropical soils and particularly those associated with land use transition zones and riparian strips (Erickson and Keller, 1997; Dick et al., 2008). Bowden (2000) reported that uncertainty in the mass balance of the atmospheric N_2O budget was approximately 30%. Consequently, N_2O flux determination in different ecosystems is necessary to enable the accurate validation of both global and regional N_2O source-sink models. Despite their potential importance, there are few reports of N_2O production in riparian systems worldwide and none in the tropics. This study therefore aimed to determine seasonal variation of N_2O emissions from a tropical riparian ecosystem in contrasting with spatial patterns of different land use types between leguminous reforestation area and agricultural area with maize and to determine the major environmental factors regulating N_2O emissions.

4.2 Materials and methods

Research methodology was already described in Chapter III.

4.3 Results

4.3.1 Tropical climatic characteristics

Figure 4.1 a, b and c displays the general climate characteristics for the experimental sites to demonstrate the strong seasonal variability. Overall relative humidity averages were approximately 80% in the wet season and 65% in the dry season. With respect to temperature patterns, both soil temperature and air temperature (minimum, average, and maximum) remained relatively constant during the wet season, but they were significantly lower during the main dry season before increasing again during May. Average soil temperature was significantly different for both land use types and seasons, and average air temperature and relative humidity were significantly different only for seasons ($P<0.05$, Table 4.1). The interaction between land uses and seasons were also significant in relation to mean air temperature and relative humidity ($P<0.05$, Table 4.1). The greatest amount of rain and highest rainfall accumulation in 1, 3, and 5 days prior to N_2O flux measurements only occurred in wet season (Figure 4.4 c).

4.3.2 Seasonal variation in different land use types

Figure 4.2 illustrates the temporal variation of inorganic soil N and total N at the experimental field sites. As the result, the availability of NH_4^+ was significantly different by season ($P<0.05$). Across the year, the availability of NH_4^+ in the soil were higher in the reforestation plots when compared to the maize plots ($P<0.05$). Conversely, the NO_3^- was significantly higher in the dry season than in the wet season ($P<0.05$); however, there was no significant impact from land use. Generally, there was a significant trend in total soil nitrogen (SON). It is indicated that the reforestation plot has significantly higher levels than the maize plots ($P<0.05$) and in the dry season compared to the wet season ($P<0.05$).

Figure 4.3 displays the temporal variation in the main soil C pools. Overall, the significant seasonal variation was seen in DOC and microbial biomass carbon in both land use types with higher concentrations apparent in the wet season relative to the dry season. Although the temporal patterns in the two land uses were similar, the size of these C pools tended to be greater in the reforestation plots relative to the maize plots, particularly in the wet season ($P<0.05$). Total soil carbon (SOC) showed no significant temporal variation, but the average SOC was higher in the reforestation plots compared to those under maize cultivation ($P<0.05$). The soil C:N ratio increased in the early wet season, but it then remained relatively constant throughout the study period (Figure 4.4 a). The interaction between factors of land use type and seasons were also significantly different with the C:N ratio ($P<0.05$).

4.3.3 Rainfall pattern and water filled pore space (WFPS)

As expected, the soil WFPS showed a significant seasonal trend in response to seasonal rainfall patterns ($P<0.05$), rising to approximately 60-70% in the wet season and falling to approximately 10-35% in the dry season (Figure 4.4 b and c). Overall, the proportion of WFPS in the soil was higher in the reforestation plots than to the maize cultivated soil throughout the year ($P<0.05$). WFPS also varied due to the interaction between land use type and seasons ($P<0.05$). Many factors clearly indicated as the regulators of denitrification (e.g., soil C:N ratio, available C and N, WFPS, river depth, and soil water table depth) were all closely correlated with rainfall accumulation (Table 4.2).

4.3.4 Spatial variation of denitrification and N_2O flux

For the whole year, the average field and laboratory estimated rates of N_2O emissions and denitrification were significantly greater in the reforestation plots than in the maize plots ($P<0.05$, Table 4.1, Figures 4.5, and 4.6). There was also a significant interaction between land use type and season for N_2O flux ($P<0.05$, Table 4.1). Significant differences in the $N_2O:N_2O+N_2$ ratio were also apparent between seasons ($P<0.05$, Table 4.1, Figure 4.7). Overall, N mineralisation and nitrification rates were significantly higher during the dry season compared to the wet season ($P<0.05$). Also, a significant effect of land use on N mineralisation and nitrification was apparent ($P<0.05$) (Table 4.1, Figure 4.8 a).

4.3.5 Correlation between the rates of N cycling, N_2O emissions, and environmental variables

Many environmental variables are strongly correlated with both rates of N cycling and N_2O emissions (Table 4.2). N_2O emissions indicated a notable positive correlation with WFPS (R = 0.48, $P<0.01$), denitrification rate (R = 0.41, $P<0.01$), relative humidity (R = 0.34, $P<0.01$), microbial biomass-C (R = 0.34, $P<0.01$), rainfall accumulation in 1, 3, and 5 day prior to N_2O flux measurement (R = 0.30-0.34, $P<0.01$), available NH_4^+ (R = 0.14, $P<0.01$), total soil C (R = 0.14, $P<0.01$), air temperature (R = 0.10, $P<0.05$), and sand content (R = 0.09, $P<0.05$). Conversely, a weak negative relationship with N_2O emissions was apparent for soil temperature (R = -0.13, $P<0.01$), clay (R = -0.11, $P<0.05$), and silt content (R = -0.10, $P<0.05$).

Denitrification rates were positively correlated with WFPS (R = 0.64, $P<0.01$), microbial biomass-C (R = 0.52, $P<0.01$), rainfall accumulation in 1, 3, and 5 day prior to N_2O flux measurement (R = 0.30-0.61, $P<0.01$), relative humidity at study site (R = 0.37, $P<0.01$), air temperature (R = 0.28, $P<0.01$), nitrate (R = 0.29, $P<0.01$), DOC (R = 0.19, P<0.01), soil temperature (R = 0.17, $P<0.01$), total soil C (R

= 0.11, $P<0.05$), and soil C:N ratio ($R = 0.11$, $P<0.05$). Conversely, denitrification was negatively correlated with soil bulk density ($R = -0.10$, $P<0.05$). $N_2O:N_2O+N_2$ ratio was not correlated with the rates of nitrification, but it did increase as denitrification and N_2O emission decreased ($R = -0.47$ and -0.16, $P<0.01$).

A significant correlation was apparent between nitrification rates and other environmental variables including N mineralisation ($R = 0.88$, $P<0.01$), total soil C ($R = 0.36$, $P<0.01$), total soil N ($R = 0.36$, $P<0.01$), soil pH ($R = 0.19$, $P<0.01$), and available NH_4^+ ($R = 0.13$, $P<0.05$). On the other hand, nitrification rate was significantly negatively correlated with soil C:N ratio ($R = -0.29$, $P<0.01$), air temperature ($R = -0.22$, $P<0.01$), soil temperature ($R = -0.16$, $P<0.05$), 5 day rainfall accumulation prior to N_2O flux measurement ($R = -0.17$, $P<0.01$), and 3 day rainfall accumulation prior to N_2O flux measurement ($R = -0.14$, $P<0.05$).

Monte Carlo Tests indicated highly significant relationships between the 3 responding variables (N_2O flux, denitrification, and nitrification) and environmental variables for all four axes ($P=0.002$). An RDA biplot (Figure 4.9) illustrated the correlation patterns of responding variables and environmental variables by the four axes of total 58% (30.3%, 22.4%, 3.4%, and 1.9% of the 4th, 1st, 2nd, and 3rd axes, respectively). The variance in the responding variables can be explained by WFPS ($P=0.002$), N mineralisation ($P=0.002$), 5 day rainfall accumulation ($P=0.002$), reforestation ($P=0.002$), clay ($P=0.002$), bulk density ($P=0.004$), 1 day rainfall accumulation ($P=0.008$), soil temperature ($P=0.004$), wet season ($P=0.002$), soil pH ($P=0.038$), and $N_2O:N_2O+N_2$ ratio ($P=0.042$).

4.3.6 Direct emission factor (EF)

At harvesting, the average and standard deviation of maize cob yield were 5.7±2.9 t dry matter (DM) ha^{-1} combined with a vegetative residue of 6.1±3.4 t DM ha^{-1}. The total N derived from the sum of residual maize crop (90.85±51.19 kg N ha^{-1} $yr^{-1)}$ and applied fertilizer N (175 kg N ha^{-1} yr^{-1}) was 265±51.19 kg N ha^{-1} yr^{-1}. While average annual N_2O emissions from maize cultivation was 2.2 kg N ha^{-1} y^{-1}. Then, EF for agriculture with maize was 0.008 kg N_2O–N (kg N input)$^{-1}$ and ranges 0.01-0.007 kg N_2O–N (kg N input)$^{-1}$.

In reforestation, ground litter was 0.62±0.16 t DM ha^{-1} and average amount of N fixed by the leguminous trees was 55±15 kg N ha^{-1} y^{-1}. While the average annual N_2O emissions from the reforestation area was 3.3 kg N ha^{-1} y^{-1}, Therefore, EF for reforestation was 0.06 kg N_2O–N (kg N input)$^{-1}$ and ranges 0.047-0.083 kg N_2O–N (kg N input)$^{-1}$.

Table 4.1 N_2O emissions and environmental conditions of the tropical riparian experiment plots.

Parameters	Unit	Land use types		Seasons	
		Reforestation	Maize	Wet	Dry
N_2O emissions^{abc}	$\mu g\ N_2O\text{-}N\ m^{-2}\ h^{-1}$	37.20±1.52	25.47±0.93	37.66±1.50	24.93±0.91
Denitrification^{ab}	$mg\ N_2O\text{-}N\ kg^{-1}\ h^{-1}$	0.0028±0.0002	0.0024±0.0002	0.0037±0.0002	0.0006±0.0001
$N_2O : N_2O + N_2$ ratio^{b}	Ratio	1.31±0.14	1.07±0.15	0.99±0.12	1.63±0.18
Net N mineralisation^{ab}	$mg\ N\ kg^{-1}\ h^{-1}$	0.227±0.029	0.149±0.025	0.153±0.024	0.258±0.033
Net Nitrification^{ab}	$mg\ NO_3^-N\ kg^{-1}\ h^{-1}$	0.018±0.001	0.012±0.001	0.014±0.001	0.017±0.001
Microbial biomass carbon^{ab}	$mg\ C\ kg^{-1}$	757.55±27.22	634.20±21.41	851.77±26.50	542.76±16.64
Dissolved organic carbon^{ab}	$mg\ C\ kg^{-1}$	46.49±1.38	40.50±1.29	48.03±1.60	39.07±0.97
Total soil C^{a}	%	1.78±0.02	1.49±0.01	1.63±0.02	1.64±0.02
Total soil N^{ab}	%	0.128±0.003	0.094±0.002	0.101±0.003	0.122±0.002
C:N ratio^{abc}	Ratio	15.09±0.32	17.47±0.47	18.72±0.52	13.84±0.12
NH_4^{+ab}	$mg\ NH_4^+\text{-}N\ kg^{-1}$	4.88±0.16	3.90±0.13	4.61±0.14	4.19±0.16
NO_3^{-b}	$mg\ NO_3^-\text{-}N\ kg^{-1}$	10.78±0.51	10.20±0.54	9.45±0.49	11.53±0.55
Soil pH (H_2O)^{b}		6.15±0.01	6.19±0.01	6.13±0.01	6.21±0.02
Gravimetric soil water content^{abc}	%	18.41±0.54	13.87±0.52	22.54±0.43	9.83±0.33
Bulk density^{a}	$g\ cm^{-3}$	1.35±0.01	1.33±0.01	1.34±0.01	1.34±0.01
Porosity^{a}	%	48.90±0.26	49.98±0.25	49.43±0.27	49.43±0.24
WFPS^{abc}	%	50.28±1.36	36.96±1.40	60.58±1.09	26.96±0.92
Clay^{a}	%	20.86±0.14	20.51±0.09	nd	nd
Silt^{a}	%	47.71±0.59	52.13±0.48	nd	nd
Sand^{a}	%	31.43±0.70	27.37±0.52	nd	nd
Soil texture^{ns}		Loam	Silt loam	nd	nd
Soil temperature at study sites^{ab}	ºC	26.67±0.18	28.29±0.22	28.99±0.14	25.94±0.23
Air temperature at study sites^{bc}	ºC	25.50±0.18	25.59±0.20	27.53±0.13	23.56±0.15
Relative humidity at study sites^{bc}	%	73.44±0.85	72.55±0.81	81.69±0.56	64.32±0.71
Minimum 1 day rainfall^{ns}	mm	0.0	0.0	0.0	0.0
Maximum 1 day rainfall^{ns}	mm	12.0	12	12.0	0.0
Minimum 3 day rainfall^{ns}	mm	0.0	0.0	0.0	0.0
Maximum 3 day rainfall^{ns}	mm	73.9	73.9	73.9	0.0
Minimum 5 day rainfall^{ns}	mm	0.0	0.0	4.0	0.0
Maximum 5 day rainfall^{ns}	mm	108.5	108.5	108.5	0.0

The values presented are mean and standard error of mean (SME); rainfall values are minimum and maximum. The superscript letters (a, b, and c) indicate that mean variation is significantly different (*P*<0.05) by land use type, season, and their interactions. The superscript letters (ns) indicate no statistical analysis was undertaken. The letters (nd) indicate not determined.

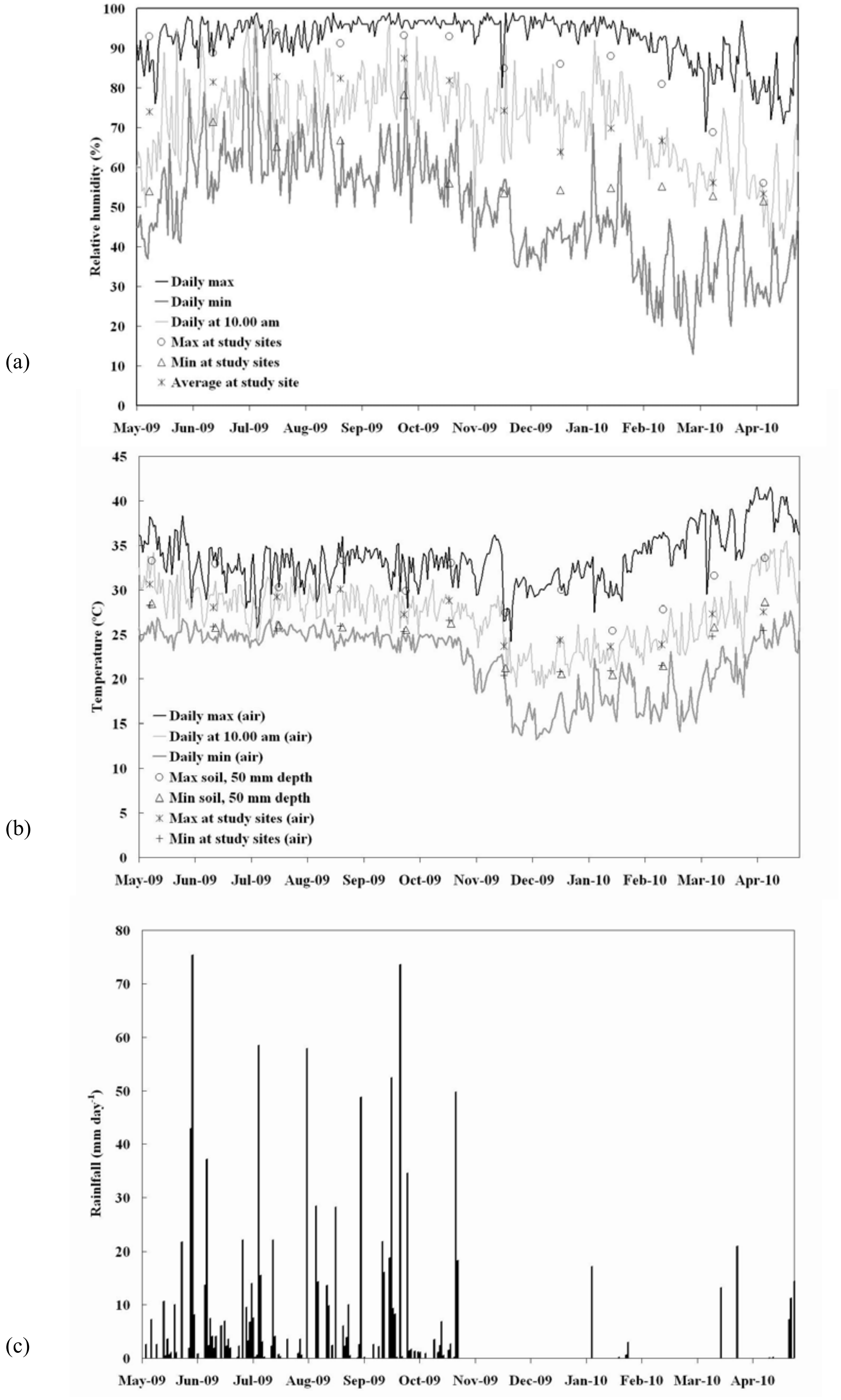


Figure 4.1 (a) Relative humidity; (b) air temperature; and (c) daily rainfall of the three experimental riparian study sites.

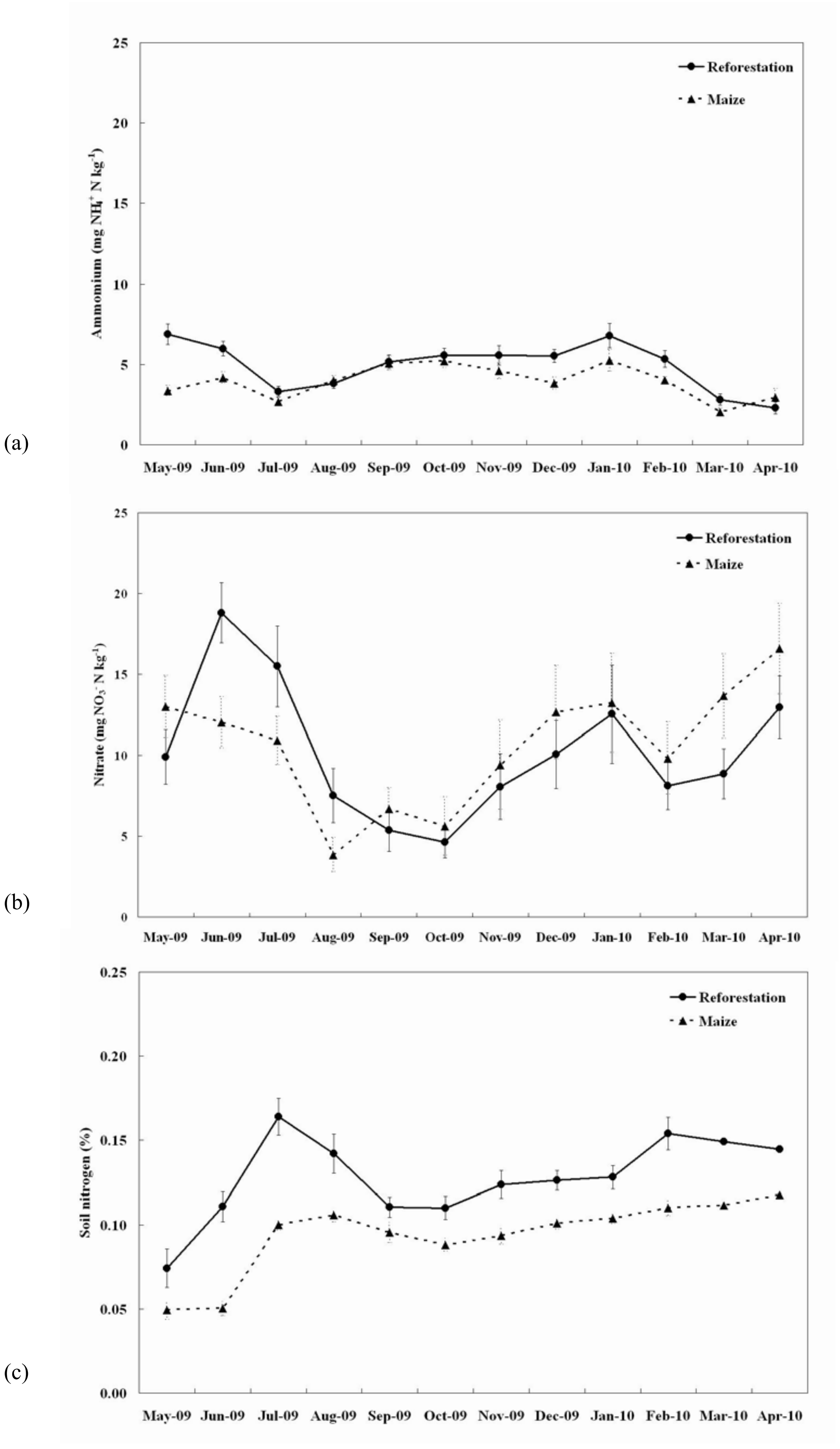


Figure 4.2 (a) Available ammonium; (b) available nitrate; and (c) total soil nitrogen in the reforestation (mean ± SEM, *n* ≤23) and maize area (mean ± SEM, *n* ≤22).

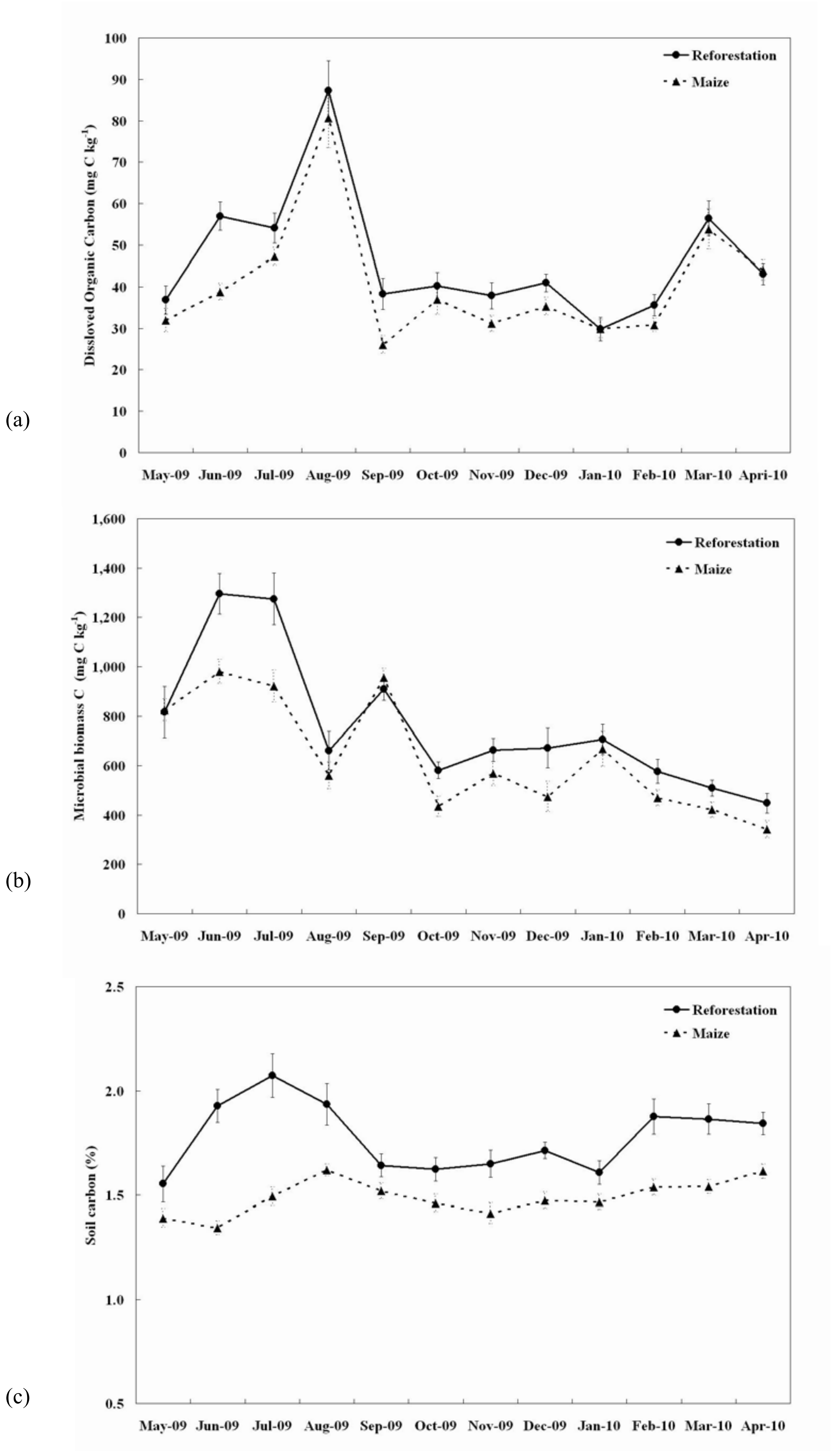


Figure 4.3 (a) Dissolved organic carbon; (b) microbial biomass carbon; and (c) total soil carbon in the reforestation (mean ± SEM, *n* ≤23) and maize area (mean ± SEM, *n* ≤22).

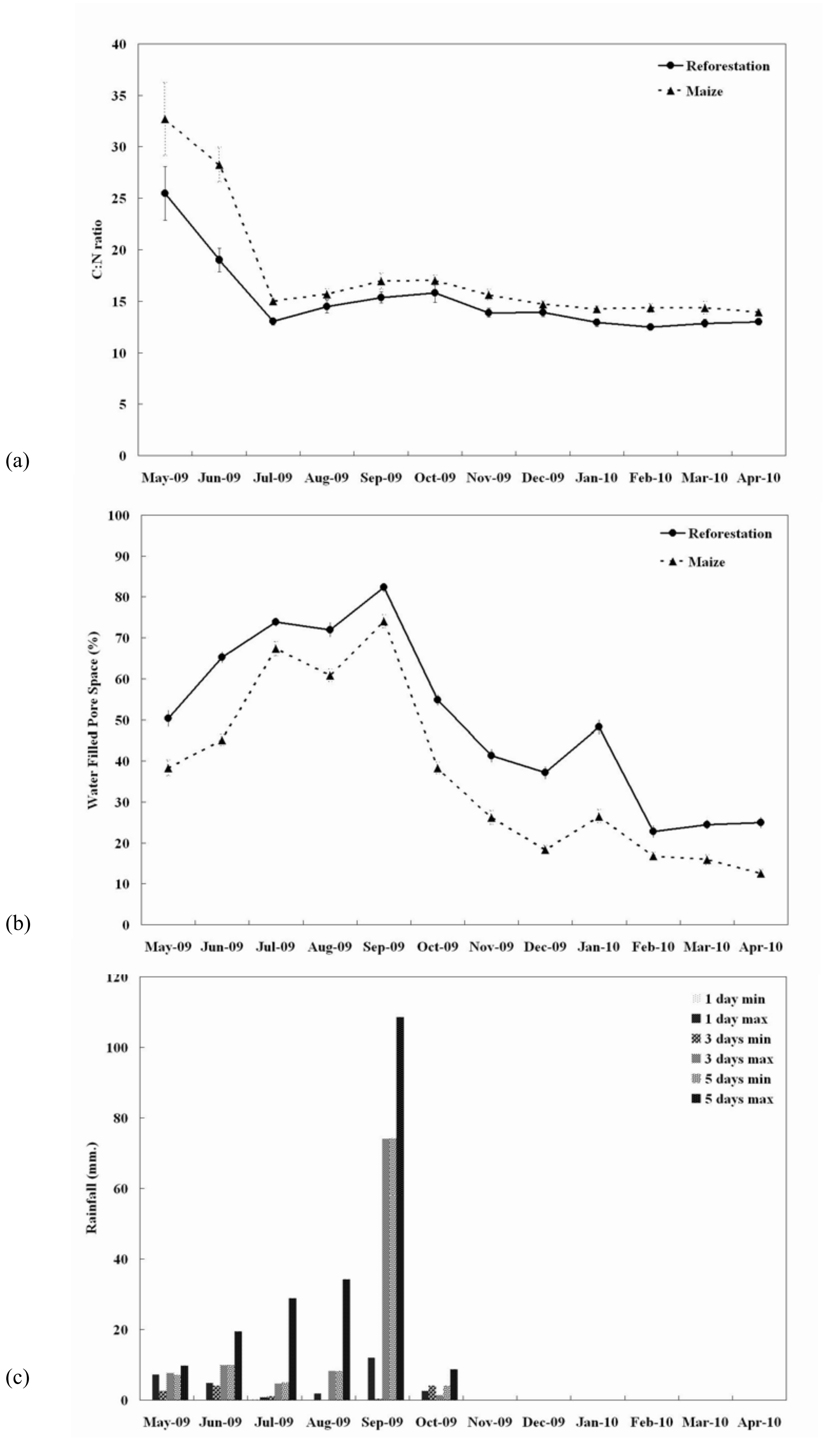


Figure 4.4 (a) C:N ratio; (b) Water Filled Pore Space (WFPS) in the reforestation (mean ± EM, $n \leq 23$) and maize area (mean ± SEM, $n \leq 22$); and (c) 1, 3, and 5 day rainfall accumulation..

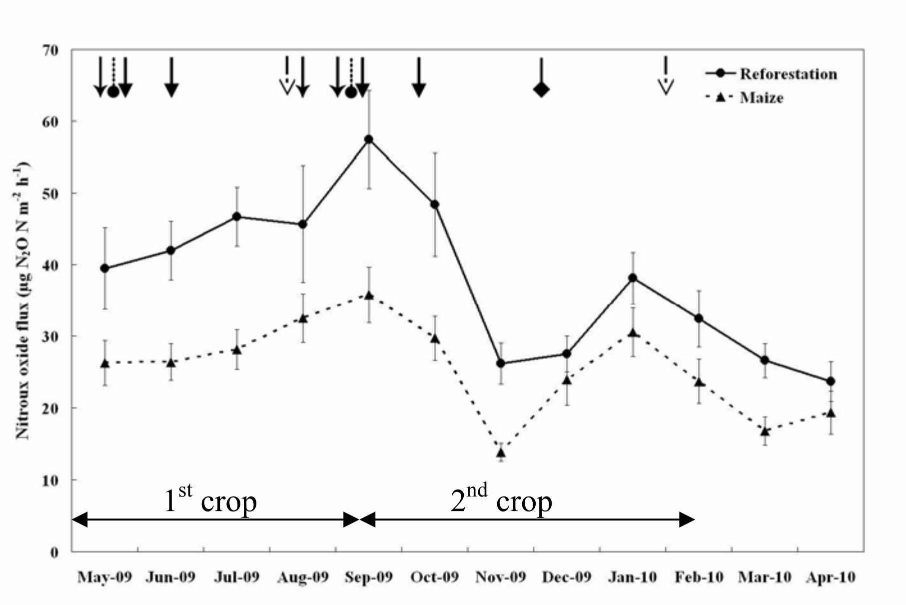


Figure 4.5 N_2O flux from the reforestation (mean ± SEM, *n* ≤23) and the maize area (mean ± SEM, *n* ≤22) alongside key management activities in maize plot; plowing (↓), maize seeding (●), fertilizer applied (↓), maize harvesting (⇣), and lac insect and timber harvesting (◆).

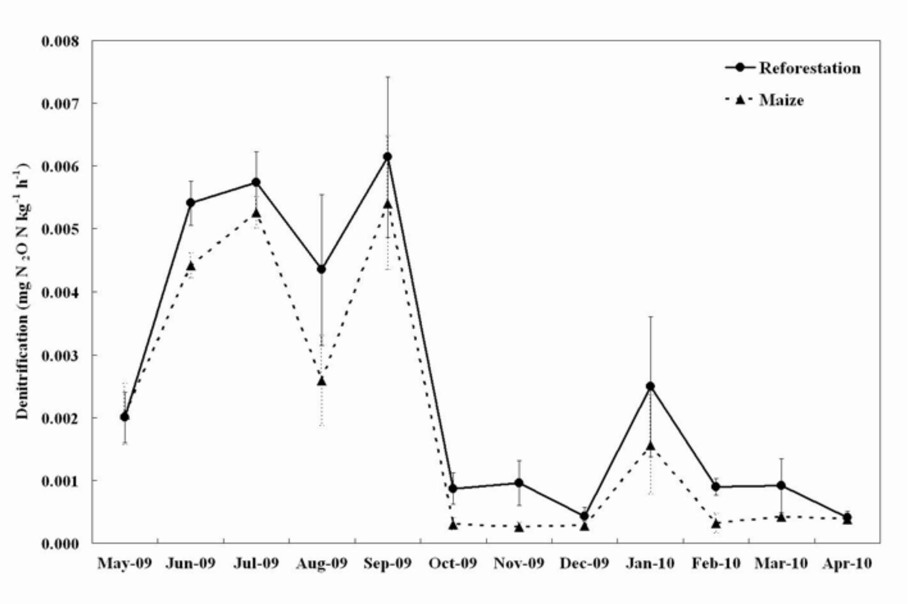


Figure 4.6 Denitrification from the reforestation (mean ± SEM, *n* ≤23) and maize area (mean ± SEM, *n* ≤22).

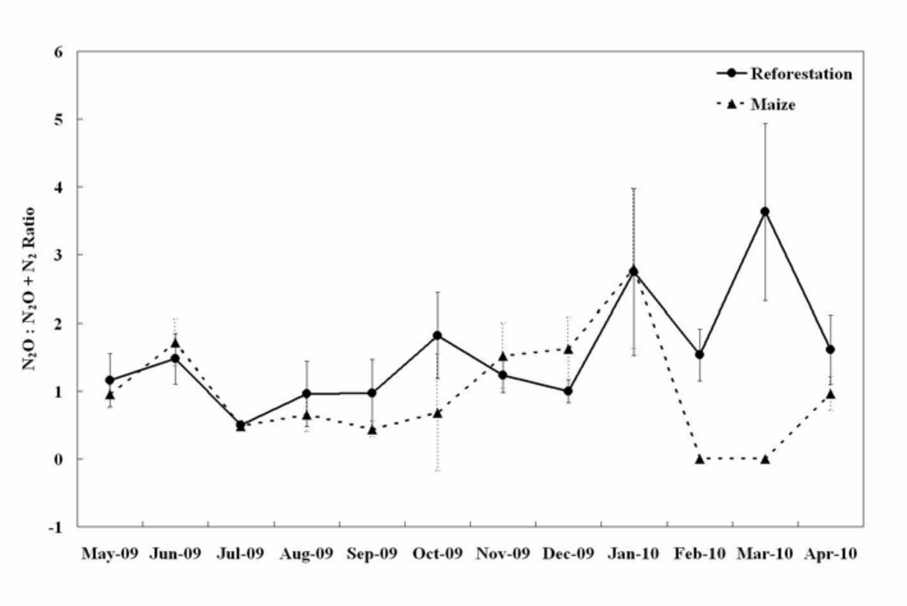


Figure 4.7 N_2O:N_2O+N_2 ratio from the reforestation (mean ± SEM, *n* ≤23) and maize area (mean ± SEM, *n* ≤22).

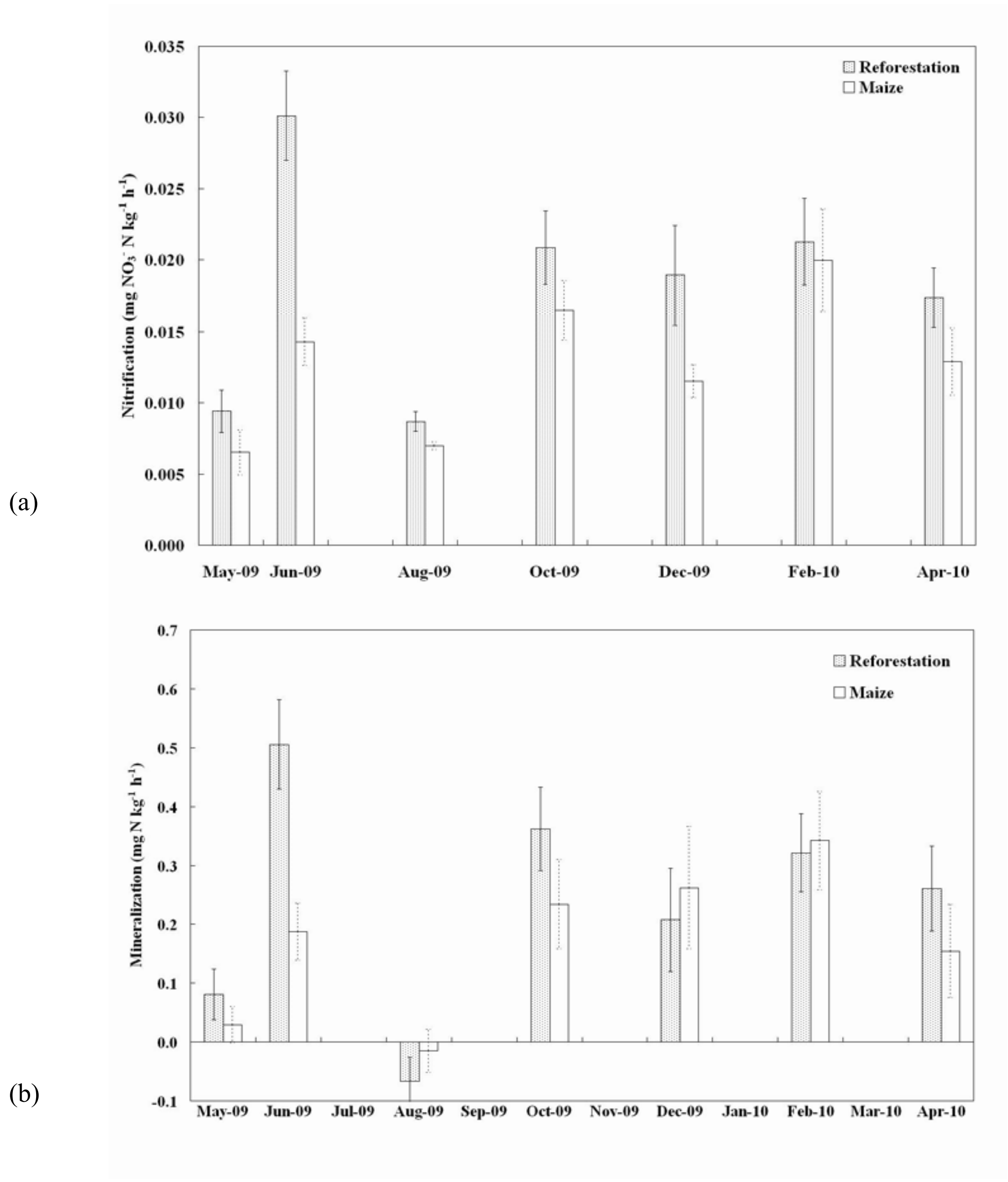


Figure 4.8 (a) Net nitrification and (b) Net N mineralisation in the reforestation (mean ± SEM, *n* ≤23) and maize area (mean ± SEM, *n* ≤22).

Table 4.2 Spearman's rho correlation coefficient among N_2O flux, denitrification, nitrification, and environmental conditions.

Parameters	N_2O emission (n = 540)	Denitrification (n = 415)	Nitrification (n=255)
N_2O emission (n = 540)	1.00	0.41^{**}	0.02
Denitrification (n = 415)	0.41^{**}	1.00	-0.07
Net nitrification (n=255)	0.02	-0.07	1.00
N_2O:N_2O+N_2 ratio (n=380)	-0.16^{**}	-0.47^{**}	0.09
Net N mineralisation (n=250)	-0.08	-0.13	0.88^{**}
Microbial biomass carbon (n=260)	0.34^{**}	0.52^{**}	0.04
Dissolved organic carbon (n=540)	0.02	0.19^{**}	0.03
Total soil carbon (n=540)	0.14^{**}	0.11^{*}	0.36^{**}
Total soil nitrogen (n=537)	0.04	-0.001	0.36^{**}
C:N ratio (n=532)	0.06	0.11^{*}	-0.29^{**}
NH_4^+ (n=539)	0.14^{**}	-0.02	0.13^{*}
NO_3^- (n=536)	0.06	0.29^{**}	0.06
Bulk density (n=540)	0.05	-0.10^{*}	-0.09
WFPS (n=540)	0.48^{**}	0.64^{**}	-0.09
1 Day rainfall (n=540)	0.32^{**}	0.30^{**}	0.006
3 Day rainfall (n=540)	0.30^{**}	0.49^{**}	-0.14^{*}
5 Day rainfall (n=540)	0.34^{**}	0.61^{**}	-0.17^{**}
Soil temperature (n=540)	-0.13^{**}	0.17^{**}	-0.16^{*}
Air temperature (n=540)	0.10^{*}	0.28^{**}	-0.22^{**}
Relative humidity (n=540)	0.34^{**}	0.37^{**}	-0.04
Clay (n=540)	-0.11^{*}	-0.04	0.00
Silt (n=540)	-0.10^{*}	-0.04	-0.05
Sand (n=540)	0.09^{*}	0.03	0.05
Soil pH (n=540)	0.08	0.01	0.19^{**}

The single asterisk (*) and double asterisk (**) indicate significant R values at the levels of significance of $P<0.05$ and $P<0.01$, respectively.

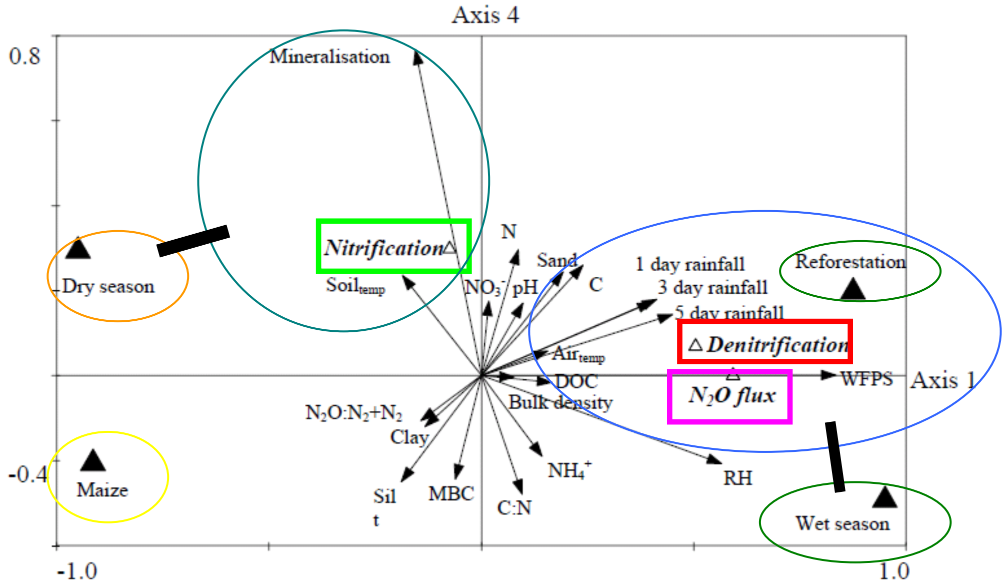


Figure 4.9 RDA biplot of the N_2O flux, denitrification and nitrification as response variables and environmental variables. WFPS is water filled pore space. 1, 3, 5 day rainfall are 1, 3, 5 day rainfall accumulation before the N_2O measurement. $Soil_{temp}$ is soil temperature at 50 mm depth. Air_{temp} is air temperature at study site. C is total soil carbon. N is total soil nitrogen. C:N is C:N ratio, DOC is dissolved organic carbon. MBC is microbial biomass carbon. pH is soil pH. $N_2O:N_2O+N_2$ is the $N_2O:N_2O+N_2$ ratio. RH is relative humidity.

4.4 Discussions

4.4.1 Seasonal variation of N_2O flux

The N_2O flux patterns indicated a significant difference of temporal fluctuations between wet and dry seasons. The highest peaks of N_2O emission occurred during the wet season due to the combination of rainwater occupying the soil void space, the application of N fertilizer to the agricultural areas and the rapid mineralisation of N in the reforestation area. This is exemplified by the N_2O flux in September 2009 being approximately 3-fold higher than in May 2009. The lowest N_2O emissions occurred in the dry season from November 2010 to March 2011 when no rainfall occurred. This study found that N_2O emissions took place in the early wet season were consistent with studies in other ecosystems (Byrnes et al., 1993; Davidson et al., 1993; Dobbie et al., 1999; Garcia-Montiel et al., 2003; Butterbach-Bahl et al., 2004; Van Haren et al., 2005; Werner et al., 2006). In terms of the key controllers driving N_2O production, it is confirmed that microbial biomass carbon and available N both significantly increased following the first rainfall event at the start of the wet season and corresponded with peak emissions (Davidson et al., 1993). In the middle of the wet season, This study found that WFPS and soil temperature also appeared to play a major role in regulating N_2O production in agreement with Weitz (2001) and Schaufler et al. (2010). Previous studies have also shown that N_2O emissions increased exponentially with increasing WFPS (Keller and Reiners, 1994; Castellano et al., 2010) and soil temperature (Schindlbacher et al., 2004; Schaufler et al., 2010) according to a Gaussian function corresponding to the theory of anaerobic zone development (Smith et al., 2003). It is a consequence of decreasing O_2 diffusion and reducing condition within the soil due to increasing WFPS in soil and coupled with increasing soil temperature. This may stimulate soil microorganism respiration and create suitable condition for denitrifying bacteria activity to increase denitrification rate. Although soil temperatures were at its peak again in the late dry season from March till April 2010, N_2O fluxes did not because of the low level of soil water content.

4.4.2 Land use control of N_2O emission

N_2O emitted at a WFPS of approximately 35-60% and 60-70% is the by-product of nitrification and denitrification, respectively (Bateman and Baggs, 2005). At a WFPS of more than 80-90%, denitrifying bacterial consume oxygen from N_2O as an electron acceptor and produce N_2 gas (Veldkamp et al., 1998). Such reports were used as criteria to calculate the proportion of nitrification and denitrification causing N_2O emissions. Here it is estimated that denitrification produced 50% N_2O and 18.5% N_2, whilst nitrification produced 31.5% N_2O. After the WFPS had reached 70-80% in the wet season almost all N_2O emissions proved to be the by-product of denitrification, as indicated by the Spearman's rho correlation coefficient, RDA analysis and biplot.

This result was confirmed by the low level of N_2O:N_2O+N_2 ratio in the wet season in which the N_2O:N_2O+N_2 ratio decreased with increasing total gas production (N_2O+N_2) (Groffman et al., 2000). Elmi et al. (2003) reported that a higher N_2O:N_2O+N_2 ratio indicates the nitrification process may have contributed to the N_2O flux because N_2O easily diffuses in the atmosphere, and N_2O is not further reduced to N_2 by denitrifying organisms (Webster and Hopkins, 1996). Moreover, under some circumstances (e.g. fluctuating ground water level), high levels of N_2O are not produced from nitrification due to limited O_2 levels in soil pores (Cooke et al., 2008). N_2O emissions by nitrification were found in the early wet season and most of the dry season. This period experiences rainfall stimulating the conversion of organic N to NH_4^+ but is combined with a low water table resulting in aerobic zones within the soil profile (Wang and Ree, 1996; Barton et al., 2008).

The addition of N fertilizer has often been shown to greatly stimulate N_2O production. In this study, however, N_2O emissions from the maize fields where N fertilizer have been frequently applied were not higher than those of the adjacent reforestation areas. Based on previous studies it is speculated that N inputs from N fixation do not represent an immediate source of the N_2O (Dick et al., 2006; IPCC, 2006; IPCC, 2007; Barton et al., 2011). Instead, it is more likely that the higher N_2O emissions in the forestry areas result from the change in land use or management strategy which can lead to significant alterations in organic N mineralization and soil physical structure (Rochette and Janzen, 2005). This is supported by the higher rates of N mineralisation rates in the reforestation area than in the agricultural areas and visible changes in soil structure in the afforestation areas. High soil moisture contents and low temperatures under the tree canopy, combined with N rich leaf litter and high rates of root turnover through the wet season may therefore have enhanced N and C turnover in the soil.

This result can be proposed that the factors enhancing the mineralization as the direct source of N_2O emission in this study are soil water content which is varied by accumulated rainfall, shallow ground water level, and root zone depth. General trees and maize have root depths about 2-3 m (Gasson and Cutler, 1990) and 0.15 m., respectively. Clearly, the high amounts of rainfall and soil water content were found with high impacts in wet season. The average shallow ground water level was also increased in wet season. The plant have chances to take advantage of using shallow ground water and the nutrients when subsurface water moves laterally pass root zone (Correll, 1997). Also, high moisture content in soil and stable low level temperature by tree canopy through wet season may enhance nitrogen and carbon turn over rate by microorganism via decomposition, minimization, nitrification, and denitrification, thus increasing N_2O production and emission in reforestation (von Arnold et al., 2005). Comparatively in riparian wetland plant strip has higher N_2O emission than that without plant cover (Hernandez and Mitsch, 2006).

N_2O emissions are strongly related to soil NO_3^- (Groffman et al., 2000; Hefting et al., 2003; Vilain et al., 2010). Farmer applied urea as N fertilizer 2 times in May and June 2009. Urea is hydrolysis with in 1-2 days and oxidized to NH_4^+ and NO_3^- occurred after 7 days (Dawar et al., 2011; Serrano-Silva et al., 2011). Therefore, there was only observed a strong correlation between NO_3^- and N_2O emissions for the first two months of the wet season. This result suggests that NO_3^- availability to the soil microbial community was generally not limiting N_2O production (Adviento-Borbe et al., 2010). It should be noted that the soil NO_3^- reported here were much higher than reported in previous riparian zone studies which indicated a positive correlation between the N_2O flux and NO_3^- (Ullah and Zinati, 2006; Vilain et al., 2010). Similarly, this study suggests that soil organic C was not a limiting factor for denitrification. The DOC in both the reforestation and maize experimental areas was estimated to be between 100 and 150 mg C l^{-1}, respectively. This compares to the threshold value of 12-15 mg C l^{-1} of DOC which is deemed sufficient to drive denitrification (Gambrell et al., 1975; Obenhuber and Lowrance, 1991). Starr and Gillham (1993) reported that an increased denitrification rate can regularly occur in the presence of shallow groundwater tables (depth <2-3 m) due to the ready supply of labile DOC. This assumption was supported by the observed C:N ratio of the soil of 15.1 ± 0.3 in the reforestation area and 17.5 ± 0.5 in the maize fields. Denitrification preferentially occurs at a C:N ratio lower than 25 (Ernfors et al., 2007; Saari et al., 2009). In summary, data from this study provides evidence showing that due to the abundance of C and N in the soil, WFPS was the main driver of N_2O emissions caused by denitrification.

4.4.3 Comparison of N_2O fluxes among the tropical riparian zone, temperate riparian zone, and other ecosystems

Several annual N_2O emission studies from different land use types in tropical riparian zone, temperate riparian zone, terrestrial tropical zone, and terrestrial temperate zone are with in the range of 0.6-26.3 (Bowden et al., 1992; Hadi et al., 2000; Towprayoon et al., 2005; Melling et al., 2007; Couwenberg et al., 2010), -0.2-4.0 (Weller et al., 1994; Hefting et al., 2003; Dhondt et al., 2004; Ullah et al., 2005; Boeckx and Van Cleemput, 2006; Hernandez and Mitsch, 2006; Kim et al., 2009; Czóbel et al., 2010; Danevcic et al., 2010; Kløve et al., 2010), 0.03-9.3 (Watanabe et al., 2000; Erickson et al., 2002; Khalil et al., 2002; Ishizuka et al., 2005; Dick et al., 2006; Werner et al., 2006; Hadi et al., 2008; Mapanda et al., 2010), and 0.13-4.97 (Chen et al., 2000; Czóbel et al., 2010; Schaufler et al., 2010; Barton et al., 2011) kg N_2O N ha^{-2} yr^{-1}, respectively. It is remarked that N_2O emission from specific studies is higher than normal ranges of peat drained agricultural land in land use change (Couwenberg et al., 2010), riparian forest with high nitrate loading (Hefting et al., 2003), and high level inorganic N in grass land European soil (Schaufler et al., 2010).

Comparatively, the annual N_2O emissions from maize cultivation (2.2 kg N ha^{-1} y^{-1}) observed in this study resemble that of a temperate riparian zone (2.3 kg N ha^{-1} y^{-1}), but they are higher than those of crops and grasslands in a terrestrial tropical zone and temperate zone by approximately 1.3 times. Annual N_2O flux from the reforestation area of the tropical riparian zone (3.3 kg N ha^{-1} yr^{-1}) was close to the average N_2O flux from forest and peat riparian tropical zone (4.0 kg N ha^{-1} y^{-1}), temperate riparian zone (3.4 kg N ha^{-1} y^{-1}), terrestrial temperate zone (3.7 kg N ha^{-1} y^{-1}), and terrestrial tropical zone (3.3 kg N ha^{-1} y^{-1}) (Appendix 5).

The similar N_2O fluxes from temperate and tropical zone forest that it is likely compromising ecological process. The values of controlling factors (nitrogen, and carbon content) in temperate zones are higher than that of tropical zones. In temperate zone, nutrient is stocked in soil; therefore, N transformation is easier than in tropical zone where nutrients are contained in plants biomass. Conversely, the stable and high temperature in tropical zone may increase productivity, decomposition and nutrient turnover rate of soil more than in temperate forest (Vitousek and Sanford, 1986; Six et al., 2002), thus taking high opportunity N_2O emitted to atmosphere by high microbial activity.

4.4.4 Direct N_2O emission factor (EF)

Direct N_2O emission factor from applied chemical nitrogen fertilizer of agriculture soil with maize (0.008 kg N_2O–N (kg N $input)^{-1}$) was lower than default EF (0.01 kg N_2O–N (kg N $input)^{-1}$) introduced by the IPCC guidelines (IPCC, 2006). Because of the high variation of N_2O emission between wet and dry season, uncertainty of EF from this study were lower than the range of uncertainty (0.003-0.03 kg N_2O–N (kg N $input)^{-1}$) proposed by IPCC. N_2O EF for N-fixation by crop is unaccounted as the source of direct N_2O emission in IPCC guidelines (2006.). Previous guideline published EF for biological nitrogen fixation by crop production is 1.25% (IPCC, 1997). However, as considering only N_2O emission from N input, EF value of this study may be useful for estimate N_2O emission from leguminous reforestation.

4.5 Conclusions

This is one of the few studies to measure N_2O emissions from a tropical riparian zone. The results indicate that the land use, season, and their interaction have a significant effect on the average N_2O emission rate from the tropical riparian zone where N_2O fluxes from a reforestation area in the wet season are higher than those in an agricultural area with maize. Variations in N_2O emitted from the tropical riparian zone were related to soil properties as controlling factors including N cycling (denitrification), C cycling, soil moisture content, and microclimate. The results also indicate that when inorganic N and organic C were not limited, the observed correlations among N_2O flux, denitrification, and WFPS were significant. This study does not support an association with N-fixing leguminous trees as a cause for an increased N_2O flux. When comparing N_2O emissions from tropical riparian zones with other studies, annual N_2O emissions from a reforestation area in a tropical riparian zone is similar to that of other ecosystems. In the case of an agricultural area with maize, the N_2O emissions from this study are similar to emissions from both tropical and temperate riparian zones, but different from other systems in the terrestrial zone. This result confirm that the EF from field observation and default EF factor of N input from chemical fertilizer plus with biomass residual and leguminous reforestation is useful to apply for estimating direct N_2O emission. Finally, the emission data and soil and environmental parameter as controlling factors are very crucial to N_2O emission management and mitigation for national importance in Thailand.

CHAPTER V

THE EFFECT OF SPATIAL PROXIMITY TO RIVER AND LANDSCAPE ARRANGEMENT ON N_2O EMISSION IN TROPICAL RIPARIAN ECOSYSTEM, NORTHERN THAILAND

Abstract

The soil property gradients in spatial heterogeneity across tropical riparian zone are likely to be the cause of the variation of N_2O emission. The hypothesis is that the variation of N_2O emission would be influenced by the spatial pattern in aspect of proximity to river and the landscape arrangement of different land use types. This study aimed to examine spatial proximity and landscape arrangement of land use types along the Nan River, Northern Thailand and seasonal variation on N_2O fluxes, and to explore the effect of soil characteristics of tropical riparian zone throughout wet and dry seasons within and among reforestation of solely N-fixing trees, *Samanea saman* (Jacq.) Merr, agricultural area with maize field, *Zea mays* L., and reforested area adjacent to the maize plot. The distal proximity of N_2O fluxes of each sampling to river in a mixture transect was significantly different ($P < 0.05$) in that N_2O fluxes of each sampling location in a mixture transect was linearly decreased at field boundary then increased at river edge during both wet and dry seasons. These were correlated to the slowly decreasing amount of inorganic nitrogen and dissolved organic carbon from field boundary to river side. Conversely, WFPS and denitrification were increased in the opposite patterns of those relationships. These results indicate that lateral transfer contributes to the nitrous oxide production by denitrification across tropical riparian zone. It was proposed that spatial proximately of lateral transfer may reduce the high N_2O variation observed in landscape heterogeneity and use to determine strategies for mitigating N_2O flux at specific location and time.

Keywords: Nitrous oxide flux; Riparian ecosystem; Spatial proximity; Landscape arrangement; Lateral transfer

5.1 Introduction

Nitrous oxide (N_2O) is one of the important greenhouse gases. It depletes stratospheric ozone and contributes to global warming about 8% of the total global greenhouse gas emission. Present nitrous oxide atmospheric concentration is 319 ppb, which has been increasing significantly since 1998 approximately 11% (IPCC, 2007).

Riparian zones, spatially ecological zone between aquatic and terrestrial ecosystem, are usually provided as an ecological services. Buffer strip intercepts sediment and soil erosion from lateral flow in adjacent agricultural areas and then plant uptake and/or nitrate nitrogen have been removed by denitrification before discharging the remaining into aquatic system. Such ecological function in riparian zone is reducing water quality problems and eutrophication risks (Naiman et al., 2005). On the other hand, riparian zone is likely to be a N_2O emission source (Freney et al., 1978; Groffman et al., 2000; Verhoeven et al., 2006) because it has no limit of environmental factors (i.e. inorganic nitrogen, organic carbon, and soil water content) influencing on N_2O formation by nitrification and denitrification processes. High N_2O flux from riparian zone occurs when riparian ecosystem receives substrates from various ways. For instance, flooding and surface water runoff deposit sediments or organic matters and additional nutrients to the land (Church, 2002). Enormous inorganic nitrogen is received by the leaching process from intensive nitrogen fertilizer used in agricultural upland area (Lowrance et al., 1984; Entry and Emmingham, 1996). And the amount of oxygen indicating reduction state due to high level of soil moisture content is affected by low water table and high river water level (Naiman et al., 2005).

Ecologically, the variability of nutrient concentration and physical factors found in riparian zone is a consequence of spatial heterogeneity due to the process of disturbance such as flooding and drying, and the interaction of geomorphology and hydrology in longitudinal and lateral transfer (Fisher and Welter, 2005). For example, the lateral transfer rate of nitrogen flux concentration may vary depending on spatial heterogeneity (i.e. patch density) from upslope to river edge (Johnson et al., 1997).

Riparian buffer zones improve water quality by designing plant arrangement in lateral flow direction, with woody tree close to river and adjacent to agricultural areas that have intensive added N fertilizer. Spatial ordering would intercept sediment from runoff and increase the retention time of leaching nitrate in shallow groundwater. Although this landscape configuration design will mitigate water pollution by reducing nitrate nitrogen before loading to river, it is a source of N_2O emission. For example, riparian forest zone closed to river is likely to have lower nitrate than the area adjacent to upper zone in the agricultural area because nitrate is reduced to be N_2O by denitrification (Hefting et al., 2003).

N_2O emission study in temperate agroecosystems is widespread, but there are only few studies of N_2O emission from tropical soils, particularly those associated with land use transition zones and riparian strips (Erickson and Keller, 1997; Dick et al., 2008). Moreover, although there are various N_2O studies focusing on the land use types or various ecosystems as per spatial homogeneity assumption, the results are uncertain estimates with high N_2O variation (Pang et al., 2009). For instance, N_2O emissions from riparian wetland obtaining inorganic nitrogen from adjacent agricultural area are ranging from 0 to 45 kg N ha^{-1} y^{-1} and not likely to be related to the environmental factors that regulate optimized N_2O production by nitrification and denitrification. In addition, most publications do not incorporate the effect of spatial heterogeneity to N_2O emission in their studies (Cooke et al., 2008). Consequently, N_2O emitted from soil by denitrification and nitrification may be unequal in soil profile along lateral transfer in riparian zone due to different O_2 diffusion, and carbon and nitrogen substrates in micro pore soil due to the effect of proximal and distal controls (Groffman et al., 1988; Robertson, 1989; DeSimone et al., 2010). Accordingly, N_2O emission conducted in heterogeneity landscape of tropical riparian zone is a necessary investigation.

The hypothesis is that the variation of N_2O emission would be influenced by the spatial pattern in the aspect of proximity to river and the landscape arrangement of different land use types. The aims of this study were to quantify proximity to river and land use type arrangement on seasonal N_2O flux, and to determine the major soil properties (i.e. available nitrogen, organic carbon, and WFPS) controlling N_2O emission along lateral transfer.

5.2 Materials and methods

Research methodology was already described in Chapter III.

5.3 Results

5.3.1 Tropical micro climate

Wet and dry seasons can be distinguished due to the amount of rainfall. The wet season has received 1,023.8 mm of rainfall, while the dry season has recorded a total of 88 mm of rain, which is less than those of wet season approximately 11.6 times (Figure 5.1 a). Air temperature at 10.00 pm during wet and dry seasons was 24.3°C - 34.2°C and 19°C - 35.5 °C, respectively. Lower air temperature in dry season from November 2009 to February 2010 was observed due to north-east monsoon that introduced cool and dry weather (Figure 5.1 a). Shallow groundwater table throughout riparian zone along sampling plot decreased in dry season and increased in wet season (Figure 5.1 b). The shallow groundwater depth at all study sites interact with rainfall and river water levels. As expected, WFPS variation was associated with rainfall. High WFPS about 50-80% was related to large rainfall in wet season during early May to October 2009. Lowest values of WFPS about 10-40% due to low rainfall intensity were observed in dry season from November 2009 to April 2010 (Figure 5.1 c).

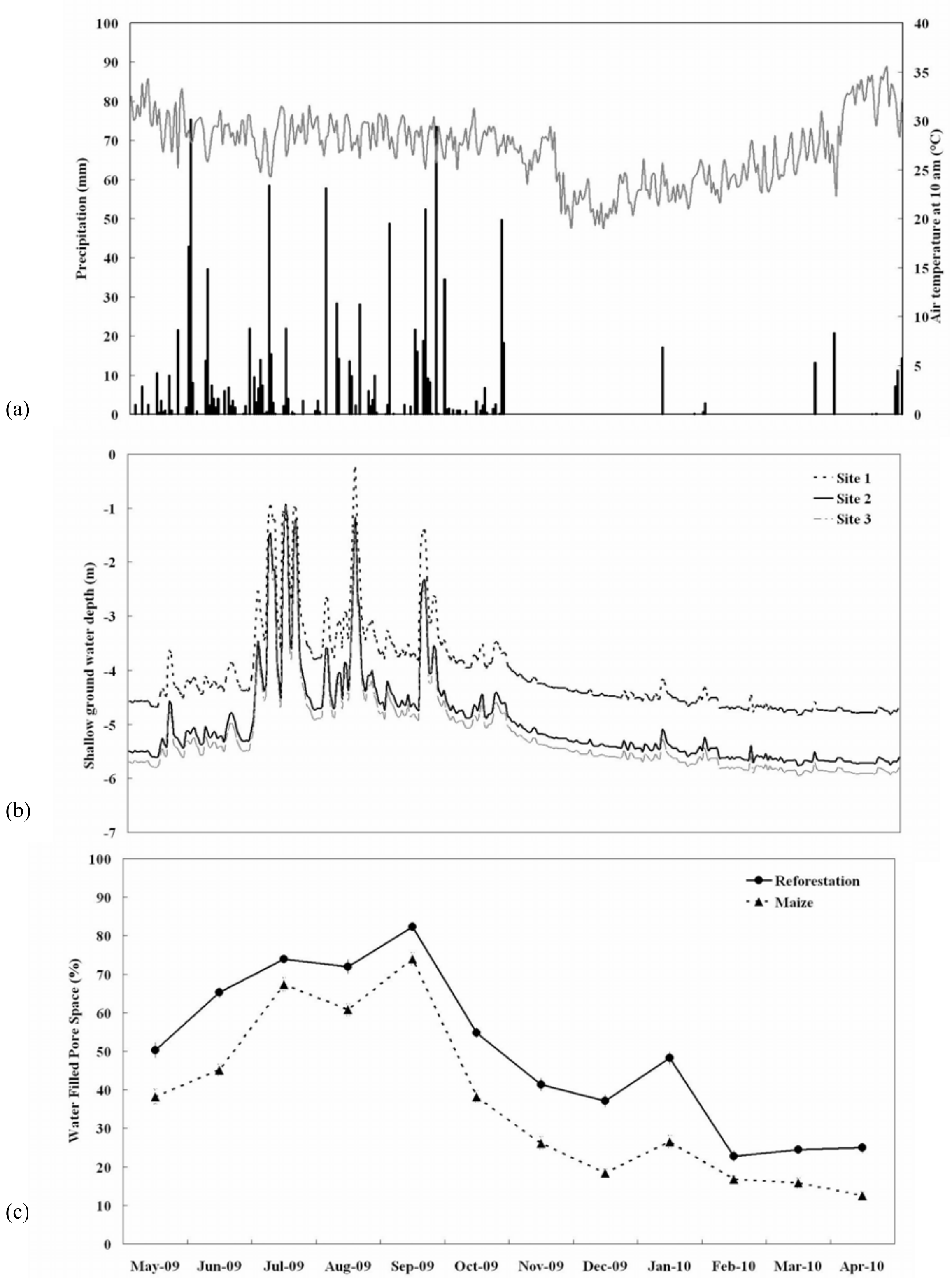


Figure 5.1 (a) Daily precipitation and air temperature, (b) shallow ground water depth, and (c) monthly WFPS in the reforestation experimental plots (mean ± SEM, *n* ≤23) and the agricultural areas planted with maize (mean ± SEM, *n* ≤22).

5.3.2 Proximity to river and spatial configuration on seasonal N_2O fluxes

N_2O flux of each sampling location within transects was observed a distinctly spatial difference for a mixture transect only in both wet and dry seasons ($P<0.05$), but they were not for reforestation and maize transects. The pattern of N_2O flux proximity to river within transects was likely a positive skew shape in wet season and a low inversed linear line in dry season (Tables 5.1 and 5.2; Figures 5.2 a and 5.2 b). During wet season, N_2O flux from a mixture and maize transects increased gradually from FB to AIR, but then decreased at RS, while the N_2O fluxes of reforestation transect from upper zone (AFI and FB) were higher than those of lower zone (RS, AIR and IZ). During dry season, the N_2O fluxes of mixture transect increased gradually from FB to RS. On the contrary, the N_2O fluxes of reforestation transect increased slowly from AFI to RS. However, the N_2O fluxes of maize transect was not related to the proximity to river along lateral flow.

From Tables 5.1 and 5.2, temporal variation among transects (all sampling positions together) showed significant difference in both wet and dry seasons ($P<0.05$). In wet season, the homogenous subset of means was distinct between maize transect (41.01 μg N_2O-N m^{-2} h^{-1}) and mixture transect (67.17 μg N_2O-N m^{-2} h^{-1}), but the N_2O flux from reforestation transect (61.03 μg N_2O-N m^{-2} h^{-1}) was in between those of maize and mixture transects. While the N_2O flux in the dry season of reforestation transect (28.78 μg N_2O-N m^{-2} h^{-1}) and mixture transect (31.68 μg N_2O-N m^{-2} h^{-1}) were homogenous and more than that of maize transect (21.25 μg N_2O-N m^{-2} h^{-1}). When considering at fine temporal scale of monthly N_2O emission across lateral flow, Figure 5.3 describes that temporal scale between monthly and seasonal observation is not distinct patterns of N_2O emission across lateral transfer.

It is indicated that the spatial proximity to river and landscape arrangement of land use in mixture transect were likely to induce N_2O flux at the geographic location close to the river.

5.3.3 Seasonal N_2O flux of each sampling position among transects

N_2O fluxes were significantly different by observing from each sampling position among transects in RS, AIR and AIF in the wet season, and RS, AIR, IZ and FB in the dry season (*P*<0.05; Tables 5.1 and 5.2; Figures 5.2 a and 5.2 b).

The rate of N_2O emissions from RS and AIR in the wet season was highest in mixture transect (reforestation area), then reforestation transect (reforestation area) and maize transect (maize field), respectively. The amount of N_2O fluxes from AIF during dry season was lowest in maize transect (maize field), then mixture transect (maize field), and reforestation transect (reforestation area), respectively.

In wet season, the N_2O flux at AFI of the two maize and mixture transects were not significantly different, but the N_2O flux from reforestation transect was significantly different higher than those two transects (P<0.05). The N_2O fluxes from RS and AIR positions in mixture transect were significant different more than those of maize and reforestation areas (*P*<0.05).

In dry season, the N_2O fluxes at RS in reforestation and mixture transects were similar, but they were significantly different from that of the maize transect (*P*<0.05). At AIR and IZ locations also showed significant difference, the N_2O flux of the reforestation area in mixture transect was higher than that of maize plot, but in reforestation area in reforestation transect the N_2O flux was classified to be same as maize or mixture transect (*P*<0.05). At FB location, the homogenous subset of N_2O flux between forest and maize transects was significantly separated, but in the mixture transect the N_2O flux was classified as a group of N_2O fluxes in both reforestation and maize transects.

5.3.4 Spatiotemporal patterns of soil properties

The variability of denitrification, nitrate, soil total nitrogen, soil total carbon, WFPS within transect, soil total nitrogen and carbon, the C:N ratio and WFPS of each sampling location among transects in wet season, and soil total nitrogen and carbon, WFPS within transects, denitrification, soil total nitrogen and carbon, C:N ratio, and the WFPS of each sampling location among transects in dry season were significantly different across riparian patches (P<0.05; Tables 5.1 and 5.2).

The significant difference of denitrification in mixture plot at lower zone (RS and AIR sampling locations) was higher than that of the upper zone (AFI and FD sampling location) ($P<0.05$; Figures 5.4 a and 5.4 b) in both wet and dry seasons. The proximity to river on WFPS was observed at mixture transect during wet season, and at maize and mixture transects during dry season. The WFPS at every sampling location in wet season was higher than that of dry season ($P<0.05$; Figures 5.5 a and 5.5 b). Conversely, nitrification during wet season was lower than that of dry season at every sampling location ($P<0.05$; Figures 5.6 a and 5.6 b). The proximity to river on nitrification was found during dry season, but not found in wet season.

Ammonium was not different within any transect in both seasons, except for the different mean among transect at AFI during wet season ($P<0.05$; Tables 5.1 and 5.2; Figures 5.7 a and 5.7 b). The variance of nitrate was detected within mixture transect during wet season and among transect at FB ($P<0.05$; Tables 5.1 and 5.2; Figures 5.8 a and 5.8 b). There was significant difference of soil total nitrogen within the mixture transect during wet season, but for both maize and mixture transects during dry season ($P<0.05$; 5.1 and 5.2). Besides, soil total nitrogen was significantly different among transects of each sampling location ($P<0.05$; 5.1 and 5.2). The analysis of variance was also significantly different among transects for DOC at AFI during wet season ($P<0.05$; Tables 5.1 and 5.2; Figures 5.9 a and 5.9 b). Soil total carbon was observed in the difference of variance within transect at mixture transect during wet season, while both maize and mixture transects were different during dry season. The means difference among transects was observed at all sampling locations ($P<0.05$; Tables 5.1 and 5.2). The C:N ratio was significantly different within maize and mixture transects during both wet and dry seasons ($P<0.05$; Tables 5.1 and 5.2). Comparing C:N ratio among transects, ANOVA showed significant difference at AIR and IZ during wet season, and AIR, IZ, AFI and FD during dry season ($P<0.05$; Tables 5.1 and 5.2).

Different spatial soil property pattern was represented by a positive skew shaped pattern in denitrification and nitrate during wet season, while nitrification and WFPS in dry season is a positive skew shaped pattern. Those spatial patterns were concurrent with N_2O flux shape represented.

Table 5.1 N_2O flux, denitrification, net nitrification and soil physical and chemical properties under the sampling location proximate to river in riparian zone observed in wet season.

Parameters	Reforestation transects					Maize transects					Mixed transects				
	1. RS	2. AIR	3. IZ	4. AFI	5. FB	1. RS	2. AIR	3. IZ	4. AFI	5. FB	1. RS	2. AIR	3. IZ	4. AFI	5. FB
N_2O flux	53.72	55.42	48.32	83.8	63.9	25.81	43.3	37.11	28.27	70.57	71.51	115	65.15	39.29	44.91
(µg N_2O N m^{-2} h^{-1})	±15.59^{ab}	±7.51^{a,*}	±3.99*	±17.90^{b,*}	±14.46*	±2.51^{a}	±9.69^{a,*}	±7.34*	±4.08^{a}	±40.19	±15.02^{AB,b}	±27.08^{B,b,*}	±16.07^{AB}	±10.85^{A,a}	±13.91^{A}
Denitrification	0.006	0.007	0.006	0.005	0.004	0.003	0.002	0.003	0.003	0.005	0.003	0.009	0.006	0.004	0.003
(mg N_2O N kg^{-1} h^{-1})	±0.001*	±0.003*	±0.002*	±0.001*	±0.001*	±0.001	±0.001*	±0.001*	±0.001*	±0.001*	±0.001^{A,*}	±0.003^{B}	±0.002^{AB,*}	±0.001^{AB,*}	±0.001^{A,*}
Net nitrificaiton	0.018	0.018	0.017	0.016	0.02	0.012	0.013	0.015	0.014	0.015	0.015	0.02	0.02	0.013	0.014
(mg NO_3^-N kg^{-1} h^{-1})	±0.003	±0.003	±0.003	±0.003	±0.004	±0.002	±0.002	±0.002	±0.003	±0.002	±0.003	±0.002	±0.002	±0.003	±0.003
NH_4^+	5.43	5.27	5.4	5.37	5.47	3.74	4.01	4.31	3.31	4.64	4.74	4.35	4.88	4.09	4.04
(mg NH_4^+ N kg^{-1})	±0.60	±0.51	±0.49	±0.57^{b}	±0.54	±0.41	±0.43	±0.45	±0.30^{a}	±0.58	±0.75	±0.56	±0.49	±0.45^{ab}	±0.40
NO_3^-	7.67	11	12.17	13.78	10.71	7.26	8.57	9.73	12.91	9.05	7.62	12.72	8.46	7.51	5.88
(mg NO_3^- N kg^{-1})	±1.80	±2.37	±2.83	±2.41	±2.42	±1.45	±1.53	±1.74	±2.67	±1.94	±1.62^{A}	±1.90^{B}	±1.57^{AB}	±1.67^{A}	±1.09^{A,*}
Total N	0.141	0.126	0.113	0.13	0.122	0.079	0.07	0.081	0.077	0.092	0.082	0.112	0.12	0.082	0.087
(%)	±0.016^{b}	±0.014^{b}	±0.012^{b}	±0.014^{b}	±0.012^{b}	±0.009^{a}	±0.007^{a,*}	±0.007^{a,*}	±0.007^{a,*}	±0.006^{b,*}	±0.008^{A,a,*}	±0.010^{B,b}	±0.010^{B,b}	±0.007^{A,a,*}	±0.008^{A,a,*}
DOC	56.6	48.7	56.56	51.56	54.9	40.04	40.84	47.51	40.23	45.6	51.81	52.69	39.04	47.34	46.99
(mg C kg^{-1})	±6.50	±4.00	±6.58^{b}	±4.74*	±7.84	±6.57	±4.42	±6.43^{b}	±2.78	±5.48	±8.17	±7.63	±2.45^{a}	±7.92	±7.44
Total C	1.92	1.81	1.74	1.89	1.84	1.34	1.4	1.49	1.44	1.53	1.51	1.74	1.85	1.5	1.54
(%)	±0.14^{b}	±0.10^{b}	±0.09^{b}	±0.12^{b}	±0.09^{b}	±0.05^{A,a}	±0.04^{AB,a}	±0.04^{B,ab}	±0.04^{AB,a}	±0.04^{B,a}	±0.06^{A,a}	±0.09^{B,b}	±0.08^{B,b}	±0.04^{A,a}	±0.05^{A,a}
C:N ratio	15.6	16.43	15.74	16.72	16.77	22.16	24.09	20.88	20.37	18.21	21.8	16.81	16.39	18.97	19.72
	±1.04*	±2.43^{a}	±0.74^{a,*}	±1.87	±1.34*	±3.76	±3.05^{b,*}	±1.82^{b,*}	±2.09*	±1.31*	±2.25*	±1.15^{a,*}	±0.88^{a,*}	±1.21*	±2.28*
WFPS	67.19	69.54	71.94	69.99	67.23	50.32	50.22	52.04	52.81	55.43	56.9	66.27	59.76	60.36	58.66
(%)	±3.41^{b,*}	±2.94^{b,*}	±3.30^{b,*}	±3.05^{b,*}	±3.50*	±4.31^{a,*}	±3.97^{a,*}	±4.38^{a,*}	±4.91^{a,*}	±4.74*	±4.72^{B,ab,*}	±4.04^{AB,b,*}	±3.85^{A,a,*}	±3.63^{AB,ab,*}	±3.93^{AB,*}

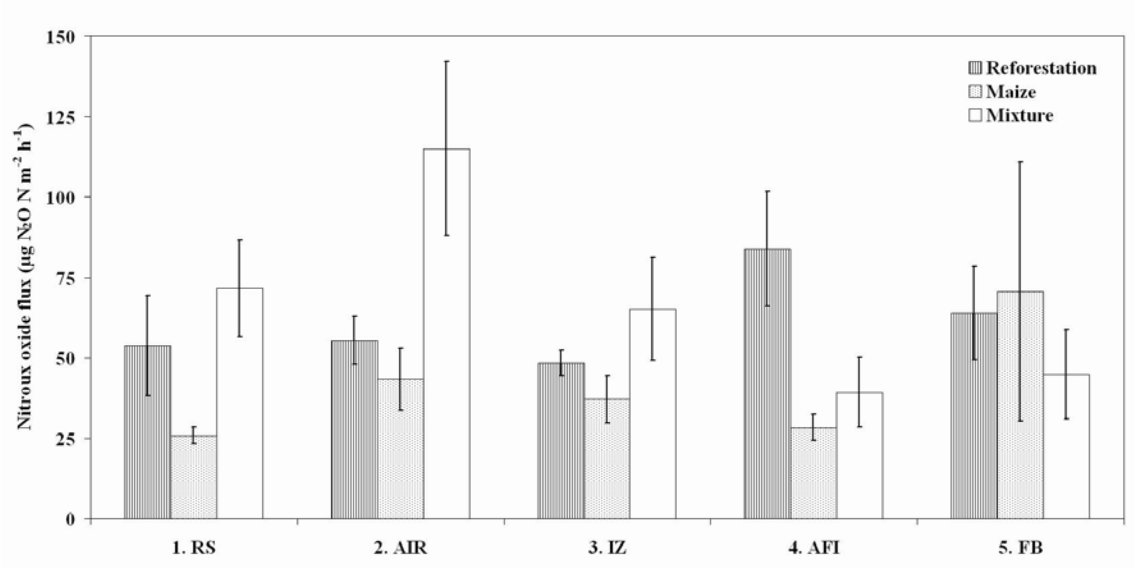
The values presented are mean and standard error of mean (SEM) for 18 samples (*n*) collected during the entire season.
The superscript capital letters and lowercase letter indicate that mean variation and homogeneous subset of each sampling location according to Dancan' post-hoc test are significantly different within transect and among transect, ($P<0.05$) respectively. The asterisk (*) indicate that mean variation is significantly different between wet and dry season ($P<0.05$).

Table 5.2 N_2O flux, denitrification, net nitrification and soil physical and chemical properties under the sampling location proximate to river in riparian zone observed in dry season.

Parameters	Reforestation transects					Maize transects					Mixed transects				
	1. RS	2. AIR	3. IZ	4. AFI	5. FB	1. RS	2. AIR	3. IZ	4. AFI	5. FB	1. RS	2. AIR	3. IZ	4. AFI	5. FB
N_2O flux	33.89	27.88	25.68	25.3	31.16	20.89	19.33	18.56	28.37	19.12	42.64	37.9	33.95	22.99	20.92
(µg N_2O N m^{-2} h^{-1})	$\pm3.99^{b}$	$\pm3.92^{ab}$	$\pm2.62^{ab}$	±2.71	$\pm4.89^{b}$	$\pm3.87^{a}$	$\pm2.52^{a}$	$\pm2.68^{a}$	±4.16	$\pm3.53^{a}$	$\pm5.31^{B,b}$	$\pm5.80^{B,b}$	$\pm4.13^{AB,b}$	$\pm3.58^{A}$	$\pm2.31^{A,ab}$
Denitrification	0.0009	0.0013	0.0013	0.0003	0.0006	0.0009	0.0001	0.0008	0.0004	0.0003	0.0011	0.0014	0.0008	0.0003	0.0003
(mg N_2O N kg^{-1} h^{-1})	±0.0004	±0.0009	±0.0005	±0.0002	$\pm0.0001^{b}$	±0.0006	±0.0001	±0.0004	±0.0001	$\pm0.0001^{a}$	±0.0006	±0.0004	±0.0004	±0.0002	$\pm0.0001^{a}$
Net nitrificaiton	0.016	0.015	0.015	0.017	0.019	0.045	0.033	0.02	0.021	0.022	0.074	0.019	0.017	0.015	0.04
(mg NO_3^{-}N kg^{-1} h^{-1})	±0.002	±0.001	±0.001	±0.001	±0.002	±0.013	±0.011	±0.007	±0.006	±0.005	±0.005	±0.003	±0.002	±0.002	±0.007
NH_4^{+}	4.82	5.88	4.66	5.26	5.1	3.94	4.47	3.53	3.46	4.3	3.95	5	3.5	3.48	4.39
(mg NH_4^{+} N kg^{-1})	±1.04	±0.91	±0.55	±0.94	±0.72	±0.59	±0.72	±0.49	±0.48	±0.60	±0.58	±0.64	±0.56	±0.49	±0.73
NO_3^{-}	12.51	11.25	9.82	12.48	7.15	12.66	11.21	10.06	11.94	14.84	10.42	13.09	13.63	9.66	12.35
(mg NO_3^{-} N kg^{-1})	±2.82	±1.95	±1.63	±2.35	$\pm0.86^{a}$	±3.00	±1.90	±2.35	±2.50	$\pm2.19^{b}$	±1.67	±2.05	±2.21	±1.87	$\pm2.09^{b}$
Total N	0.142	0.152	0.137	0.14	0.146	0.09	0.098	0.107	0.101	0.117	0.111	0.134	0.14	0.102	0.118
(%)	$\pm0.011^{b}$	$\pm0.012^{b}$	$\pm0.009^{b}$	$\pm0.009^{b}$	$\pm0.008^{b}$	$\pm0.006^{A,a}$	$\pm0.005^{AB,a}$	$\pm0.003^{BC,a}$	$\pm0.004^{AB,a}$	$\pm0.005^{C,a}$	$\pm0.007^{A,a}$	$\pm0.004^{B,b}$	$\pm0.007^{B,b}$	$\pm0.004^{A,a}$	$\pm0.004^{A,a}$
DOC	40.26	45.55	43.9	40.02	56.09	37.36	37.92	41.13	35.26	38.35	35.15	40.23	36.8	36.41	37.41
(mg C kg^{-1})	±5.31	±2.61	±3.47	±2.05	±16.05	±4.65	±2.21	±4.27	±2.69	±4.01	±3.70	±4.92	±3.91	±3.75	±3.90
Total C	1.79	1.89	1.75	1.77	1.78	1.37	1.45	1.49	1.46	1.57	1.58	1.72	1.78	1.5	1.62
(%)	$\pm0.08^{c}$	$\pm0.10^{b}$	$\pm0.08^{b}$	$\pm0.08^{b}$	$\pm0.07^{b}$	$\pm0.06^{A,a}$	$\pm0.04^{AB,a}$	$\pm0.03^{AB,a}$	$\pm0.03^{AB,a}$	$\pm0.04^{B,a}$	$\pm0.06^{A,b}$	$\pm0.04^{BC,b}$	$\pm0.05^{C,b}$	$\pm0.04^{A,a}$	$\pm0.03^{AB,a}$
C:N ratio	13.11	12.99	13.08	13.19	12.42	15.81	15.07	14.06	14.61	13.72	14.7	12.99	12.95	14.95	13.99
	±0.43	$\pm0.44^{a}$	$\pm0.39^{a}$	$\pm0.59^{a}$	$\pm0.34^{a}$	$\pm0.51^{A}$	$\pm0.50^{BC,b}$	$\pm0.28^{AB,b}$	$\pm0.36^{ABC,ab}$	$\pm0.49^{A,b}$	$\pm0.48^{B}$	$\pm0.25^{A,a}$	$\pm0.34^{A,a}$	$\pm0.58^{B,b}$	$\pm0.38^{AB,b}$
WFPS	37.33	43.09	36.01	31.42	35.16	17.18	19.13	21.12	18.06	17.07	22.75	31.64	29.12	21.75	23.57
(%)	$\pm3.15^{AB,b}$	$\pm4.43^{B,c}$	$\pm3.75^{AB,b}$	$\pm2.78^{A,b}$	$\pm2.32^{AB,b}$	$\pm2.68^{a}$	$\pm2.71^{a}$	$\pm2.90^{a}$	$\pm3.02^{a}$	$\pm2.08^{a}$	$\pm2.51^{AB,a}$	$\pm4.48^{B,b}$	$\pm3.09^{AB,ab}$	$\pm2.50^{A,a}$	$\pm2.53^{AB,a}$

The values presented are mean and standard error of mean (SEM) for 18 samples (*n*) collected during the entire season. The superscript capital letters and lowercase letter indicate that mean variation and homogeneous subset of each sampling location according to Dancan' post-hoc test are significantly different within transect and among transect, ($P<0.05$) respectively.

(a) Wet season



(b) Dry season

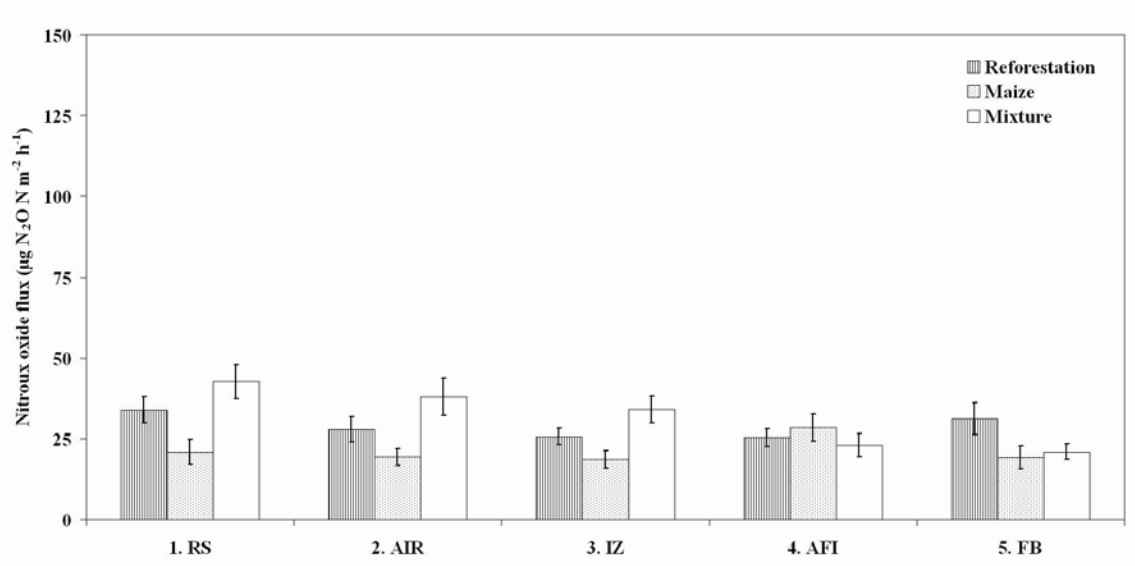
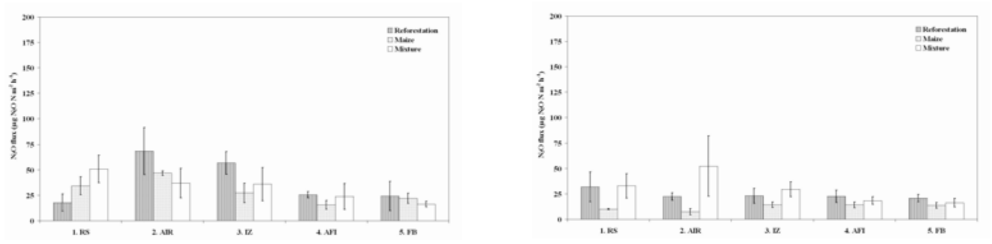
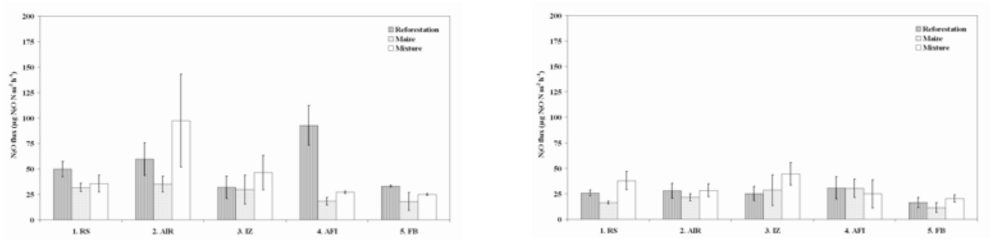


Figure 5.2 N_2O fluxes variability (mean ± SEM, *n*=18) on proximity of each sampling location to river in (a) wet season and (b) dry season.



May 2009 November 2009



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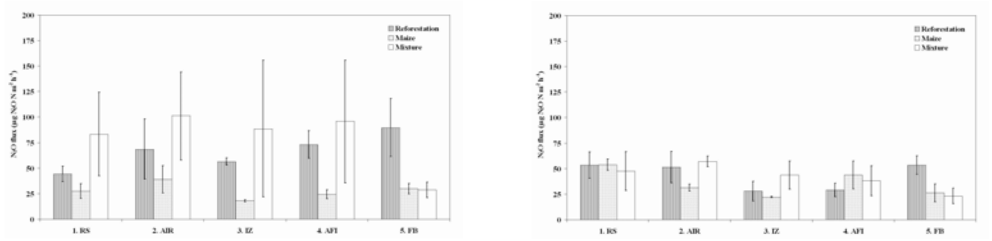

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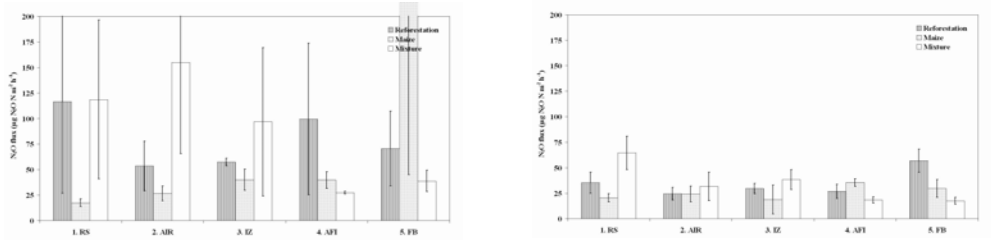

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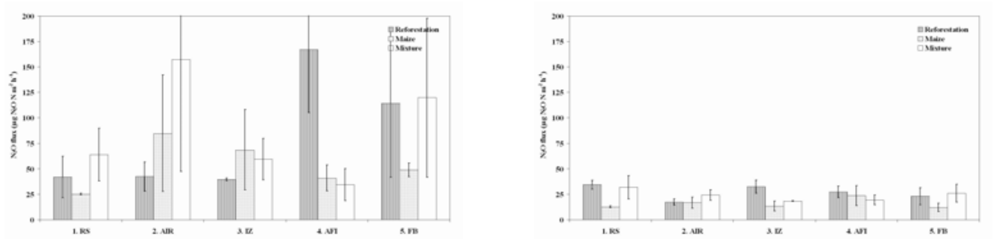
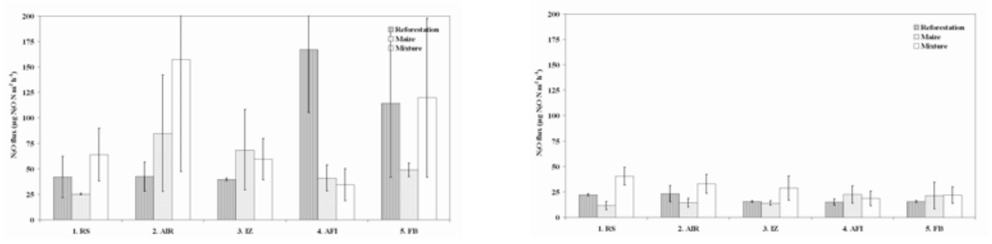


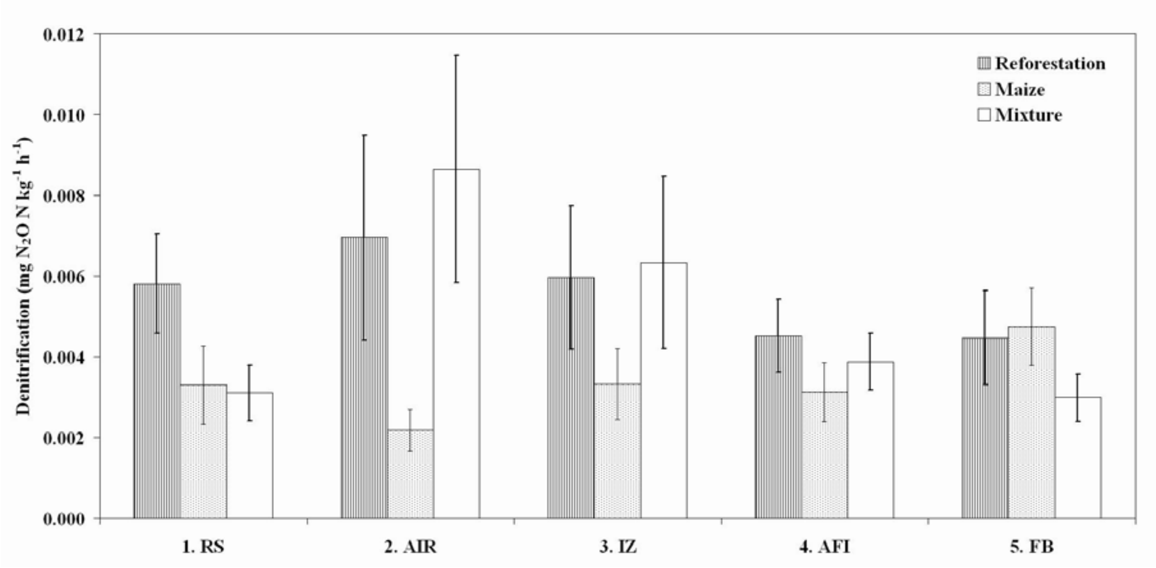
September 2009 March 2010



October 2009 April 2010

Figure 5.3 Monthly N_2O fluxes variability (mean ± SEM, *n*=3) on proximity of each sampling location.

(a) Wet season



(b) Dry season

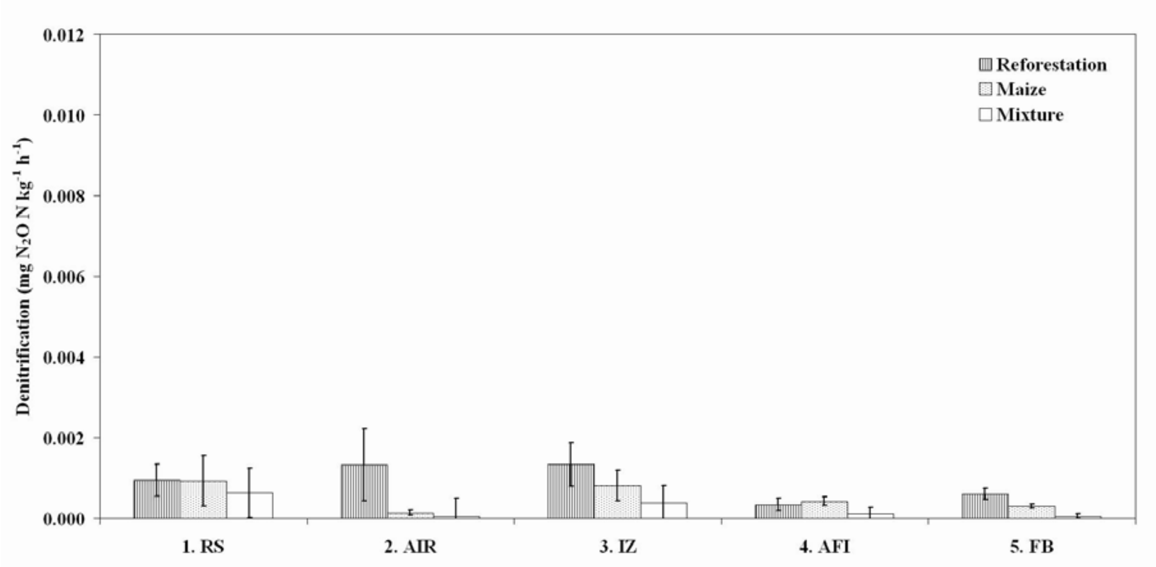
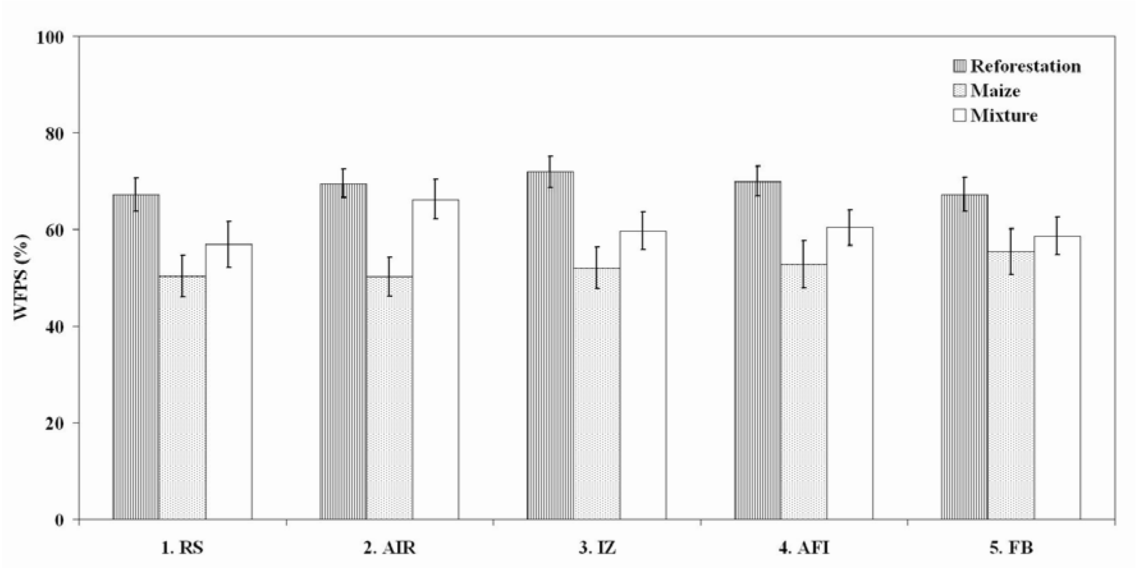


Figure 5.4 Denitrification variability (mean ± SEM, *n*=18) on proximity of each sampling location to river in (a) wet season and (b) dry season.

(a) Wet season



(b) Dry season

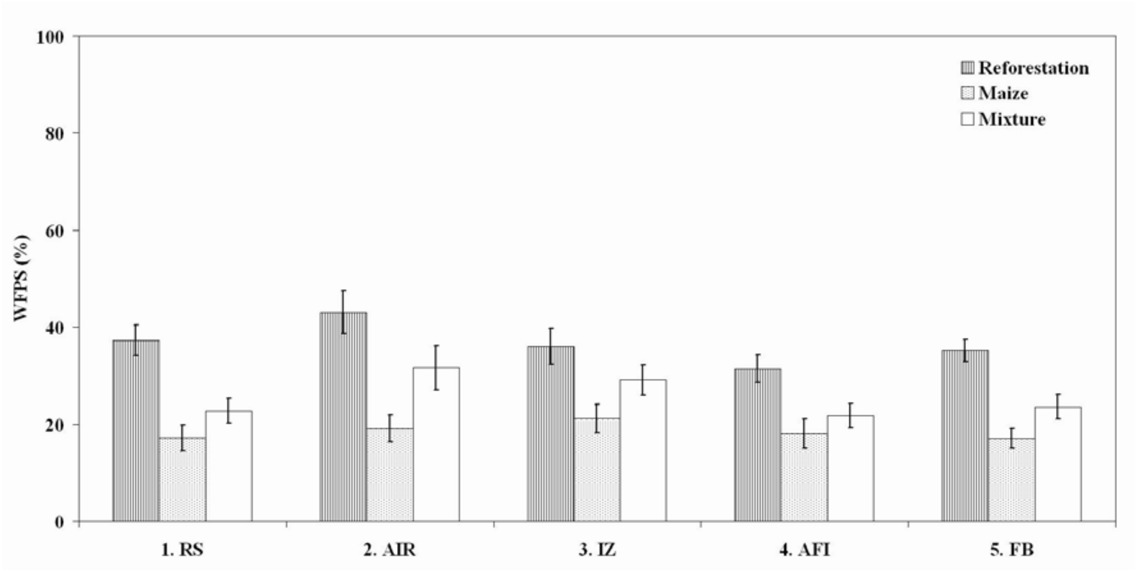
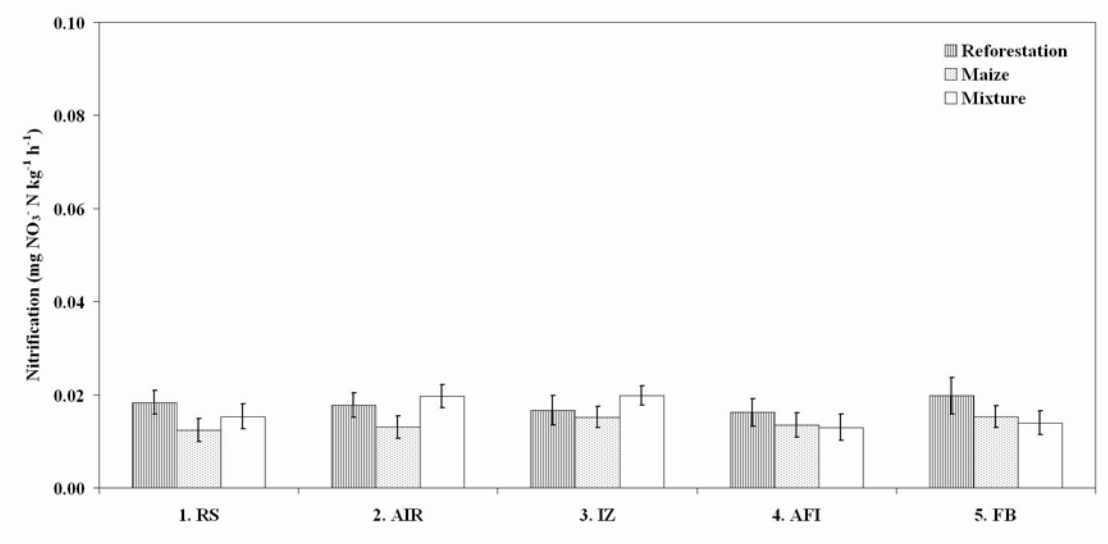


Figure 5.5 WFPS variability (mean ± SEM, *n*=18) on proximity of each sampling location to river in (a) wet season and (b) dry season.

(a) Wet season



(b) Dry season

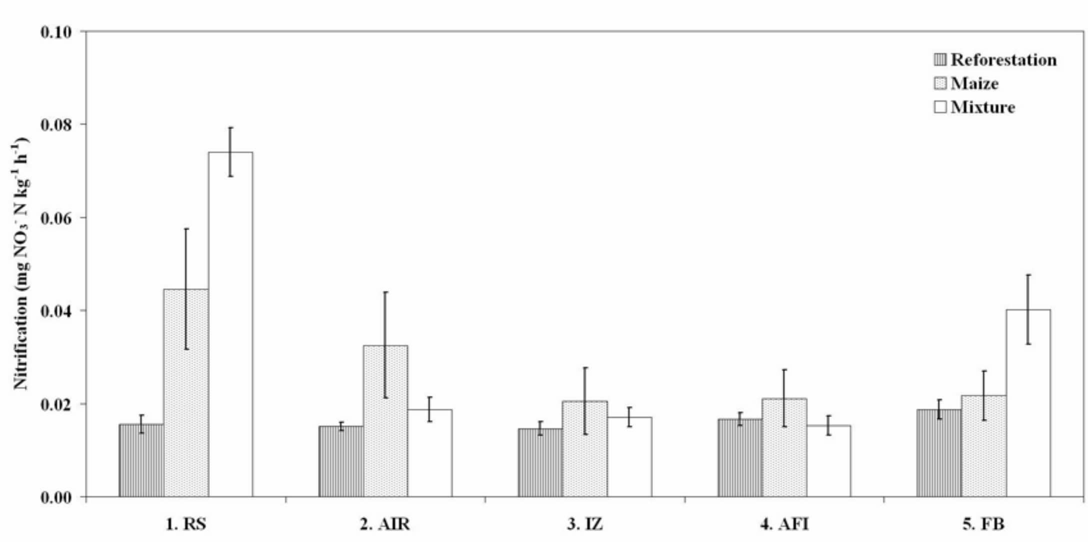
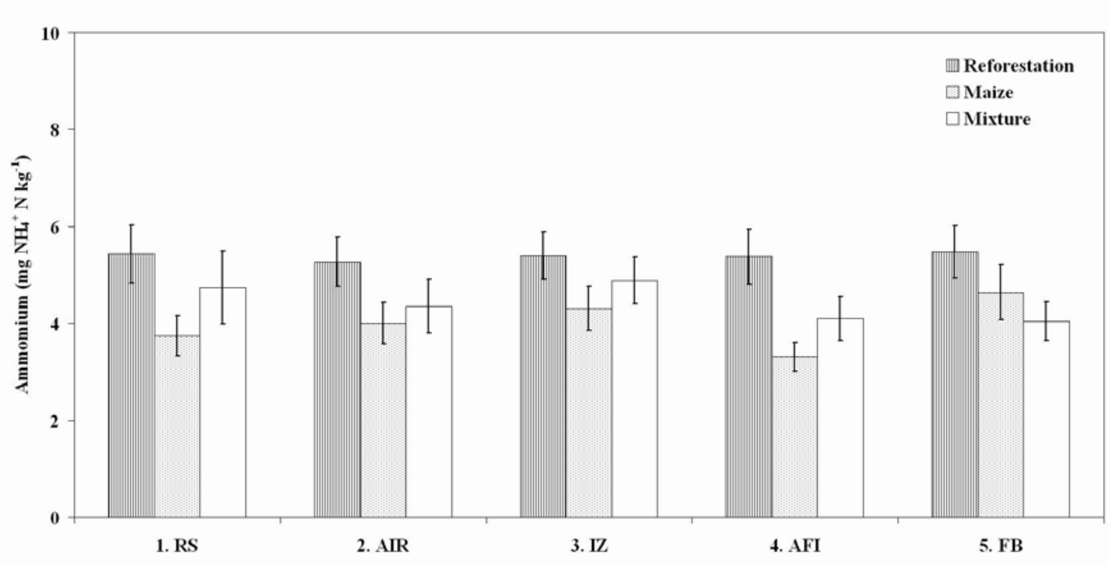


Figure 5.6 Nitrification variability (mean ± SEM, *n*=18) on proximity of each sampling location to river in (a) wet season and (b) dry season.

(a) Wet season



(b) Dry season

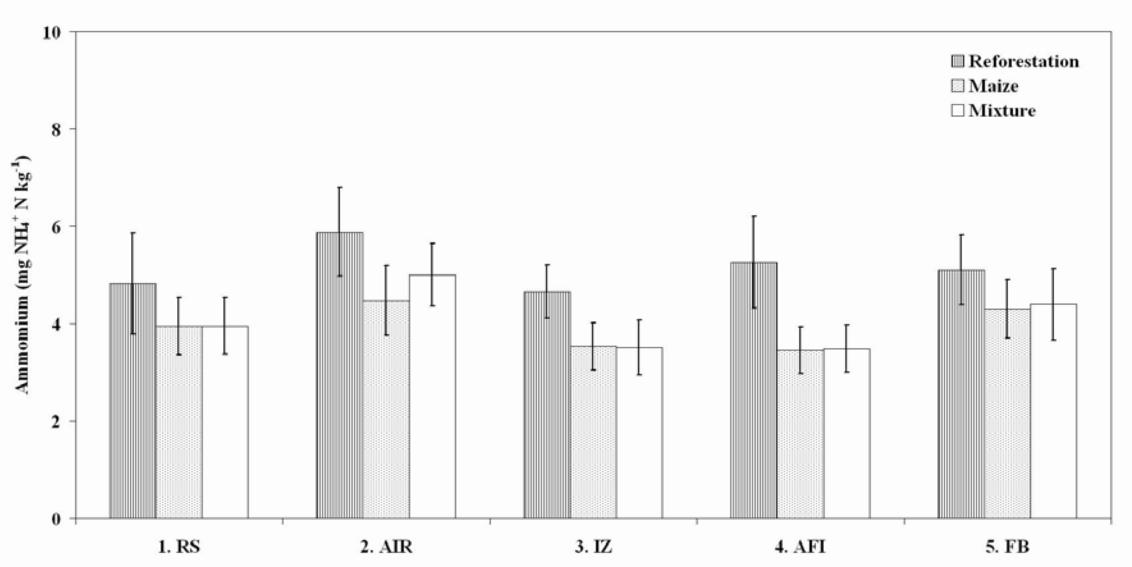
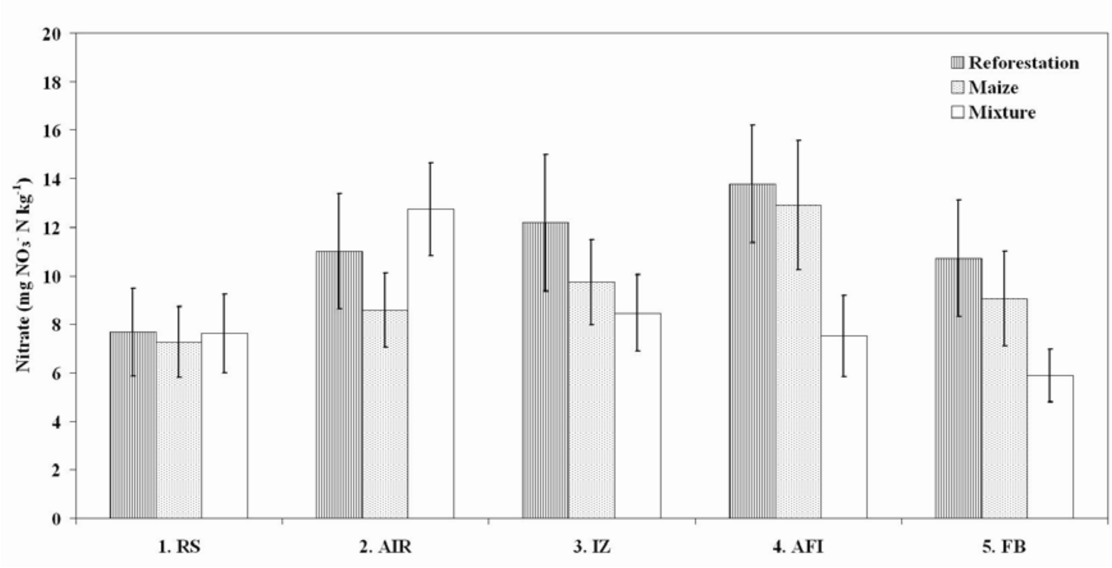


Figure 5.7 Ammonium variability (mean ± SEM, *n*=18) on proximity of each sampling location to river in wet season (a) and dry season (b)

(a) Wet season



(b) Dry season

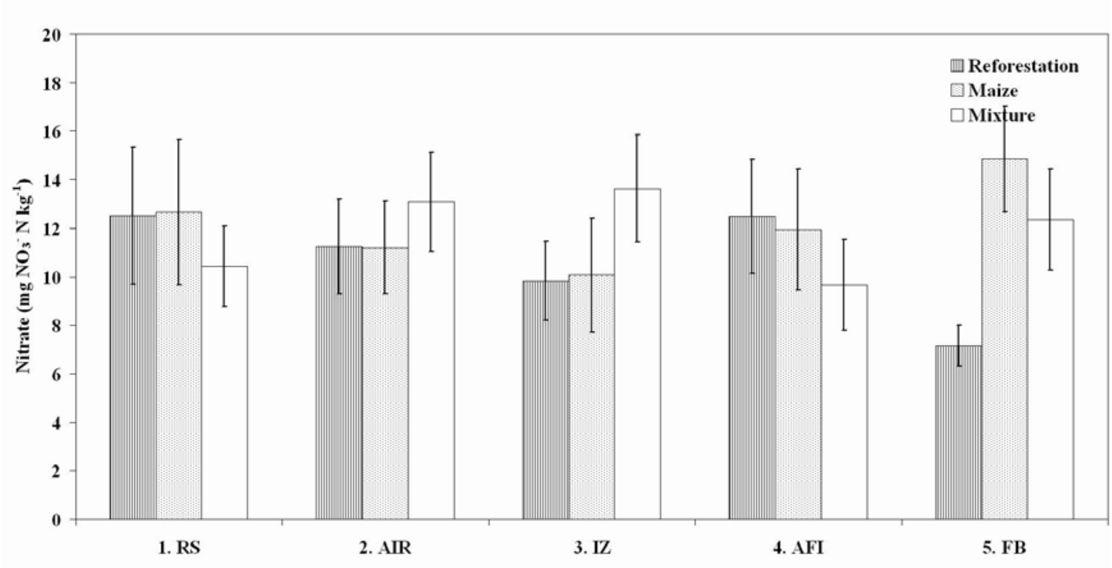
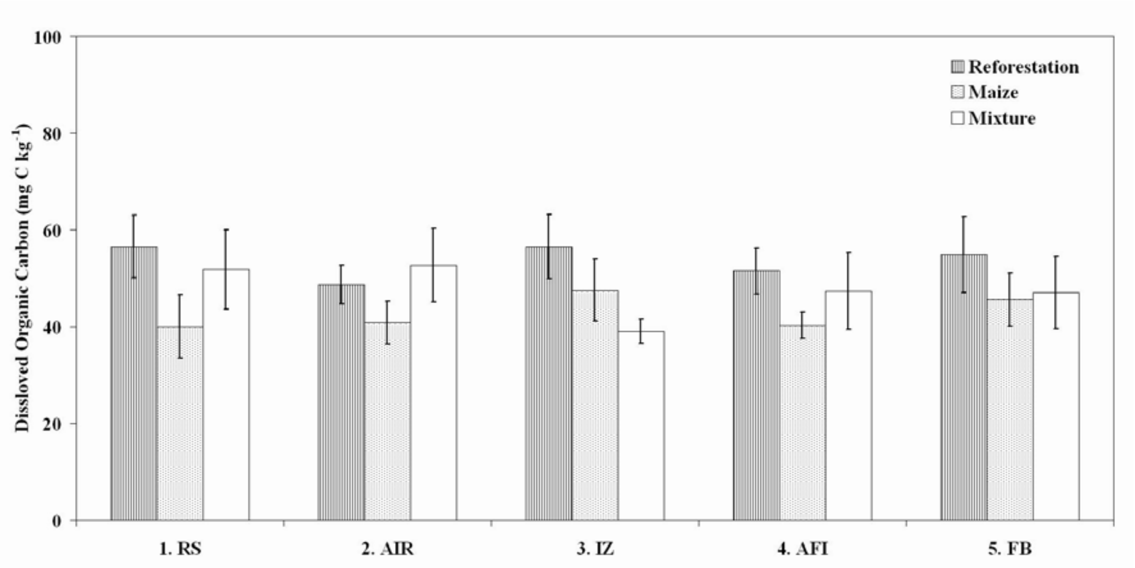


Figure 5.8 Nitrate variability (mean ± SEM, *n*=18) on proximity of each sampling location to river in (a) wet season and (b) dry season.

(a) Wet season



(b) Dry season

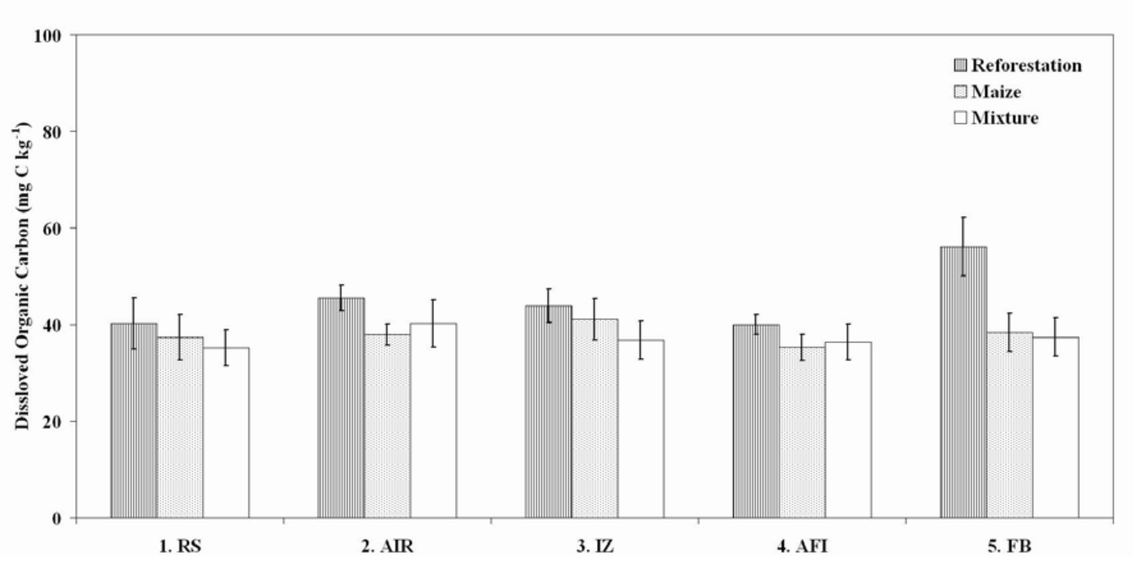


Figure 5.9 DOC (mean ± SEM, *n*=18) on proximity of each sampling location to river in (a) wet season and (b) dry season.

4.3.5 Correlation between N_2O fluxes, denitrification, nitrification and soil properties

As expected, the fluxes of N_2O emission from various sampling locations proximity to river in wet season were corresponding with the WFPS and denitrification of all sampling locations, the soil total carbon at AIR, IZ, and FB, the nitrate at RS, NH_4^+ at IZ, and the nitrification at AFI ($P<0.01$-$P<0.05$; Tables 5.3 and 5.4). Similar to dry season, the significant correlations of spatial proximity to river on N_2O were observed in same patterns as WFPS at all sampling locations, the denitrification in most locations except AFI, the inorganic nitrogen at IZ and AFI, and the soil total carbon at AFI ($P<0.01$-$P<0.05$). Highest *R* value of WFPS and denitrificaiton observed at lower zone was concurrent with N_2O flux at the same place.

The denitrification of all sampling locations in both wet and dry seasons was respected with the WFPS at every sampling location ($P<0.01$). The nitrate was associated with the denitrification at RS, AIR and AFI in wet season, and RS, AIR, and AFI in dry season ($P<0.05$). The carbon pools (Soil total carbon and DOC) were linked to the denitficaiton during wet season at AIR and IZ ($P<0.01$), and during dry season at AIR ($P<0.05$). The soil total nitrogen at AIR and the nitrification at AIR and IZ were correlated with the denitrification during wet season ($P<0.05$), while the nitrification at RS and IZ, the NH_4^+ at AFI, the C:N ratio at FB was related to the denitrification during dry season ($P<0.05$). The *R* values of dentrification were consistent with WFPS and denitrification. When the WFPS and denitrificaiton increased at lower zone or upper zone, *R* value was shown in the same pattern.

The nitrification was correlated only with the N_2O flux at AFI in wet season ($P<0.05$). Meanwhile, the nitrogen pools at AIR, IZ, AFI and FB, the soil total carbon at AIR and AFI, and the C:N ratio at AIR, AFI, and FB during wet season were related with the nitrification ($P<0.01$-$P<0.05$). During dry season, the soil total nitrogen at RS, AFI, and FB, the soil total carbon at AIR, AFI, and FB, and the C:N ratio at RS, AFI and FB were correlated with the nitrification. The *R* value between the soil total carbon and nitrogen and the C:N ration was observed at the area far from the river in the upper zone. Sampling location with high WFPS may obstruct nitrification in wet season. Figures 5.3, 5.4, 5.5, and 5.6 demonstrate that WFPS was in positive correlation with N_2O fluxes and denitrification, but in negative correlation with nitrification.

Table 5.3 Spearman's rho correlation coefficient among N_2O flux, denitrification, nitrification, and soil properties in wet season.

Sampling location	N_2O related to	*R*	Denitrification related to	*R*	Nitrification related to	*R*
1. RS	Denitrification	0.42**	WFPS	0.58**	-	-
(*n*=54)	WFPS	0.40**	N_2O	0.42**		
	NO_3^-	0.24*	NO_3^-	0.31**		
2. AIR	Denitrification	0.64**	WFPS	0.73**	Denitrification	0.27*
(*n*=54)	WFPS	0.59**	N_2O	0.64**	Soil total nitrogen	0.26*
	Soil total carbon	0.21*	NO_3^-	0.41**	Soil total carbon	0.26*
			Soil total carbon	0.39**	C:N ratio	-0.22*
			DOC	0.36**		
			Soil total nitrogen	0.32*		
			Net nitrification	0.27*		
3. IZ	WFPS	0.51**	WFPS	0.66**	Denitrification	0.28*
(*n*=54)	Denitrification	0.30**	DOC	0.31**	NH_4^+	0.23*
	Soil total carbon	0.27*	N_2O	0.30**		
	NH_4^+	0.26*	Nitrification	0.28*		
			Soil total carbon	0.23*		
4. AFI	WFPS	0.47**	WFPS	0.60**	Soil total nitrogen	0.38**
(*n*=54)	Denitrification	0.35**	NO_3^-	0.36**	Soil total carbon	0.27**
	Nitrification	0.26*	N_2O	0.35**	N_2O	0.26*
					C:N ratio	-0.30**
5. FB	WFPS	0.62**	WFPS	0.68**	NO_3^-	0.27**
(*n*=54)	Denitrification	0.39**	N_2O	0.39**	Soil total nitrogen	0.27**
	Soil total carbon	0.33**			C:N ratio	-0.25*

Note: Single asterisk (*) and double asterisk (**) indicate significant *R* values at the levels of significance of $P<0.05$ and $P<0.01$, respectively.

Table 5.4 Spearman's rho correlation coefficient among N_2O flux, denitrification, nitrification, and soil properties in dry season.

Sampling location	N_2O related to	*R*	Denitrification related to	*R*	Nitrification related to	*R*
1. RS	Denitrification	0.44**	N_2O	0.44**	Soil total nitrogen	0.26**
(*n*=54)	WFPS	0.36**	WFPS	0.43**	Denitrification	0.24**
			NO_3^-	0.34**	C:N ratio	-0.27**
			Nitrification	0.24*		
2. AIR	Denitrification	0.70**	WFPS	0.72**	Soil total carbon	0.22*
(*n*=54)	WFPS	0.59**	N_2O	0.70**		
			NO_3^-	0.43**		
			Soil total carbon	0.31*		
			DOC	0.30*		
3. IZ	WFPS	0.35**	WFPS	0.55**	Denitrification	0.29*
(*n*=54)	Denitrification	0.25*	Net nitrification	0.29*		
	NH_4^+	0.22*	N_2O	0.25*		
4. AFI	WFPS	0.30**	WFPS	0.57**	Soil total nitrogen	0.35**
(*n*=54)	NO_3^-	0.21*	NO_3^-	0.40**	Soil total carbon	0.25*
			NH_4^+	-0.27*	C:N ratio	-0.29**
5. FB	WFPS	0.49**	WFPS	0.62**	NO_3^-	0.29**
(*n*=54)	Denitrification	0.39**	N_2O	0.39**	Soil total carbon	0.24*
	Soil total carbon	0.21*	C:N ratio	0.24*	Soil total nitrogen	0.21*
					C:N ratio	-0.32**

Note: Single asterisk (*) and double asterisk (**) indicate significant *R* values at the levels of significance of $P<0.05$ and $P<0.01$, respectively.

5.4 Discussions

5.4.1 Contribution of spatial proximity to river and landscape arrangement on N_2O emission

Spatial proximity of sampling location to the Nan River on N_2O emission was gradually increased from hill slope (upper zone) toward river edge (lower zone) within mixture transect during both wet and dry seasons. Spatial trend of N_2O flux in riparian zone is expected in adjacent topographic positions between the agricultural field and riparian zone where the sediment and nutrient were carried by runoff and groundwater from upland slope toward lower area near stream edge (Groffman et al., 2000; Ullah and Zinati, 2006; van den Heuvel et al., 2009).

It was suspected that N_2O emission from different landscape arrangement on land uses, not spatial arrangement itself, was the cause of N_2O flux increasing gradually from upper zone to lower zone in the riparian ecosystem. This may lead to mistake interpretation because N_2O flux of reforested land use at lower zone was higher than maize plot. Regarding land use types, the N_2O fluxes from reforestation transect (reforestation land cover) at most sampling locations were higher than those of maize transact (maize land cover) in both wet and dry seasons. While compared with the same land cover (reforestation) at lower zone (RA, AIR and IZ), the N_2O fluxes of mixture transect were significantly higher than those of forestation transect in both wet and dry seasons. Similar to the study of Hefting et al. (2003), high N_2O emission and denitrification were observed in descending position at forest riparian strip that received high nitrogen loading from adjacent agricultural area. Thus it was suggested that high N_2O flux at mixture transects was the consequence of spatial arrangement inducing N_2O formation due to lateral flow through heterogeneous land uses combined with spatial variability of soil properties and/or influence from soil water content received from river during the dry season.

Conversely, the spatial trend of N_2O flux proximate to river was random in reforestation and maize transects in both wet and dry seasons, demonstrating that there was homogeneity of denitrification, nitrification, and soil properties in reforestation and maize transects ($P>0.05$), and different sampling positions proximate to river had no effect on the N_2O flux. This tropical riparian ecosystem in the Nan River, Northern Thailand has been used for agricultural production more than 30 years. Homogenized landscape has been induced by human disturbance during long term agricultural practices (i.e. plowing, tillage and fertilizer application). Therefore, weak spatial dependence of N_2O fluxes across slope direction was observed in agricultural area, forested soil and leguminous plantation (Ishizuka et al., 2005; Konda et al., 2008; Konda et al., 2010).

In this study, there were significant N_2O fluxes among sampling locations in both land use and seasonal comparison. This was likely the consequence of the micro scale variability in WFPS and soil properties of each sampling location itself. Burgin and Groffman (2012) found that O_2 in soil decreased when decreased distance from the stream. In this study, WFPS was relevant to the trend of spatial proximity only dry season, but did not detect such pattern in wet season. In fact, in this riparian zone there was high-level nitrate and not a limited factor for N_2O formation. The soil nitrate level examined in this study was higher than those of other riparian zone studies (Ullah and Zinati, 2006; Vilain et al., 2010). The results indicated that inorganic nitrogen and organic carbon were not limited, so topographic location at lower zone was not observed; however, gradient difference at upper zone indicates a positive correlation between the N_2O flux, denitrification and nitrate, rather than the sampling locations.

In addition, the assumption that the spatial scale used in this experiment was not optimal to detect the dependence of N_2O pattern on spatial proximity to river in reforestation and maize transects. Similar to several previous studies, they were observed that N_2O emissions were not or weak spatial dependence in riparian zone (Hefting et al., 2006; DeSimone et al., 2010), agricultural area (Clemens et al., 1999; Röver et al., 1999; Weitz et al., 1999), and forest (Ishizuka et al., 2005) with a short distance of sample points (range 1-20 m). Folorunso and Rolston (1984) and Konda (2008) proposed a distance of about 35 m were the optimal scale for observing the N_2O dependence and soil physical and chemical properties. When combining the data of N_2O fluxes from the lower zone and upper zone of the reforestation and maize transects, spatial trend was significantly related to lateral transfer from upper zone to lower positions along the slope (t-test; $P<0.05$; data not shown). Many studies also showed that the dependency of N_2O emission increased in descending degree at lower slope position (Nishina et al., 2009; Dunmola et al., 2010; Konda et al., 2010).

5.4.2 Relationship between spatial trend of N_2O emission and soil properties

Both wet and dry seasons, N_2O flux position was highest positively related to denitrification more than WFPS at RS and AIR, while at IZ AFI and FB, N_2O flux had highest relationship with WFPS, while denitrification was less apparent. It is indicated that N_2O production and emission are controlled by soil micro pore due to limited available O_2 near stream edge (Burgin and Groffman, 2012). N_2O was not associated with NO_3^- at almost sampling location excluding RS. This result is not relevant to the positive relationship of N_2O flux when applied N (Kaiser et al., 1998; Hellebrand et al., 2003; Silva et al., 2008). Reducing NO_3^- to N_2O and N_2 during denitrification is kinetic process. The rich NO_3^- in soil may induce direct N_2O production by denitrification rather than N_2O emission and N_2 may dominate as the end of production during denitrification (Mulvaney et al., 1997). Denitrification was positively related to NO_3^- in soil, and then N_2O emission was strongly connected with denitrification. Tang and Maggi (2012) explained this phenomenon that not only nitrate enrichment level dose enhance N_2O formation, but the inconstant reaction controlled by physical, chemical, and biological factors is important for reducing nitrate and N_2O emission. The observation of N_2O emission coupled with proximity sampling location to river edge reveal that spatial heterogeneity is important to explain the N_2O production and emission variation in riparian zone. This is confirmed by comparable *R* value of denitrification and nitrate categorized by sampling location being higher than those average rates of all sampling location (Tables 5.3 and 5.4)

5.5 Conclusions

The sampling location closed to the river edge was likely to have higher N_2O emssion than that of the upper zone. The N_2O variation in mixed transects was influenced by the spatial pattern of sampling locations and land use configuration that are proximately distal from river edge toward upper zone. Although lateral transfer effect to N_2O flux variation was not significantly different at reforestation and maize transects because study sites were spatial homogeneity across riparian zone, the N_2O flux variation and important controlling factors (e.g. Nitrate, DOC, and available O_2 in soil) trend are in respected with proximity to sampling location far away from the river edge. From this study, decreasing N_2O emission was in opposite trend to the increasing soil oxygen and available nitrate when distance of sampling point is toward the upper zone, while it is in positive trend to denitrification. In conclusion, N_2O emssion coupled with lateral transfer concept should be useful for understaing why the variation of N_2O flux in tropical riparian zone with spatal heterogeneity occurs.

CHAPTER VI

SIMULATION OF N_2O FLUX FROM AGRICULTURAL MAIZE IN NORTHERN THAILAND RIPARIAN ECOSYSTEM BY DNDC MODEL

Abstract

The N_2O flux rate estimation is crucial to design the management agricultural practices for mitigating N_2O emission. Due to high uncertainty and costly of N_2O experimental study, the process based models are suitable to simulate N_2O emission at site specific scale. The study site was the agricultural maize area with applied N fertilizer located along the Nan River, Northern Thailand. Testing DNDC model was performed by using initial climatic data, soil properties and agricultural practices and evaluated by observed data from filed study. Moreover, sensitivity of N_2O emission due to either increasing or decreasing of individual controlling factor was investigated. Simulated N_2O emission comparing to those observed at filed study, the model accuracy was underestimated, while model precision was slightly low. The changing of N_2O emission rate varied due to soil carbon, water filled pore space (WFPS) and amount of N applied. The results indicated that applied DNDC model for simulating N_2O emission in tropical riparian zone required model calibration for anaerobic balloon factors and nitrifying and denitrifying bacteria activities.

Keywords: Simulated N_2O emission; Process based model; DNDC; Riparian ecosystem; Northern Thailand

6.1 Introduction

N_2O emission from tropical region such as tropical rainforest and agricultural soils are an important source of global greenhouse gas emissions (Kort et al., 2011; Park et al., 2011). N_2O formation in soil is by product of microbial processes; mainly nitrification and denitrification during nitrogen cycle. The production and emission of N_2O is strongly affected to climatic condition (i.e. precipitation, temperature) (Ma et al., 2010; Smith and Owens, 2010), soil properties (i.e. pH, nitrate, texture, soil moisture content, redox potential) (Kaiser et al., 1998; Šimek and Hopkins, 1999; ŠImek and Cooper, 2002; Ruser et al., 2006; Yu et al., 2006; van der Salm et al., 2007), the interaction among plants, microorganisms and soil to nitrogen transformations (i.e. assimilation, plant nutrient uptake, nitrogen in plant production and crop residual) (Hernandez and Mitsch, 2006; Bradley et al., 2011; Dandie et al., 2011; Muhammad et al., 2011; Jacinthe et al., 2012) and land use management (i.e. applied fertilizer, crop rotation, tillage, irrigation, and drained water) (Matthews, 1994; Kaiser, et al., 1998; Guo et al., 2010; Pelster et al., 2011). Such the complex interaction and feedbacks loop among controlling factors induced N_2O emissions are high variation both spatial and temporal scales (Robertson and Grace, 2004).

The study of N_2O emission in temperate agroecosystems is widespread, but there are only few studies of N_2O emission from tropical soils, particularly those associated with land use transition zones and riparian strips (Erickson and Keller, 1997; Dick et al., 2008). The characteristic of N_2O soil–atmosphere fluxes are highly uncertain, so fine scale of measurement from hour to day and replication of sampling covered extend areas and various ecosystems are used for the reliability of emission data, thus increasing high costs for collection and analysis (Ambus et al., 2010). Also, the remote areas in which some ecosystem contributes N_2O to atmosphere are ignored (Holst et al., 2007; Zhang et al., 2010). Stimulation of N_2O emission at regional scale is needed to make decision for mitigation N_2O emission from aquatic ecosystem (Syakila and Kroeze, 2011), but it is impractical to use only N_2O emission data set from site-specific measurement. Regarding the cost of setting and maintaining field-specific flux measurement sites, applied simulation models to predict N_2O fluxes from agricultural soil system, using climatic data, soil proprieties soil, and agricultural practice calendar has balance cost/benefits. Therefore, it is important to develop tools to simulate trace gas emissions from agroecosystems by input minimal parameters. Regarding to this situation, computer simulation models covering these variables are required to analyze N_2O emission patterns in laboratory, field and regional/global levels (Chen et al., 2008). Most N_2O emission simulation models are process-based; simulating the cause-and-effect relationship between abiotic and biotic components involved the C-N biogeochemistry in agricultural soil. The examples of process based model for estimating N_2O emission at field scale are NGAS-DAYCENT, DNDC, Expert-N, ECOSYS, WNMM, FASSET, PASIM and CERES-NOE (Chen, et al., 2008; Blagodatsky and Smith, 2012). The favorable simulation model on N_2O emission from different ecosystems such as grassland, cropland, forest, and wetland is DeNitrification DeComposition (DNDC) (Abdalla et al., 2009). The DNDC model composes of two components. The first component is soil climate, crop growth, and decomposition submodels to predict soil temperature, moisture, pH, Eh, and substrate concentration in soil profiles based on ecological drivers such as climate, soil, vegetation, and agricultural activity data. The second component is the nitrification, denitrification, and fermentation submodels to predict NH_3, NO, N_2O, N_2 and CH_4 fluxes depended on the soil environmental variables. The outstanding function of DNDC model is coupled with the anaerobic balloon concept that separates anoxic and oxic parts in micro pore soil. Then, O_2 diffusion, swelling, and shrinking in soil profile are tracking. When the soil profile represents an anaerobic condition in any time step, the substrates presented in the anaerobic zone are employed in the denitrification process. This is thus allowing DNDC model simultaneously simulate N_2O formation and emission in soil profile by different sources via nitrification and denitrification with multiply environmental driving kinetic process of C and N biogeochemistry (Li, 2000).

Although N_2O emissions have been intensively measured and modelled in high input and large scale agricultural production systems at temperate region, significant uncertainty surrounds emissions from less intensive systems, particularly in tropical environments (Lokupitiya and Paustian, 2006). From previous study, we found that denitrification was strongly related to WFPS, rainfall, DOC, and NO_3^- at site-specific scale. It is indicated that these controlling factors can be challenged input into process-based models for testing the simulation of N_2O emission pattern from tropical riparian zone. Due to data collections of this study that was designed based on ecological process-based approach, it is likely suitable and sufficient for working with DNDC model. This research presented the simulation of N_2O emission by DNDC model and validated with datasets measured at three agricultural areas with maize in tropical riparian zone, the Nan River, Northern Thailand.

6.2 Materials and methods

6.2.1 Study sites

The there agricultural areas with maize sites located on riparian ecosystem at 18º37’13.04”N, 100º45’44.20”E; 18º35’04.89”N, 100º45’46.79”E; and 18º33’27.91”N, 100º45’46.29”E were used for field measurement. The experiment plots were 100 m in length at 90° to the river and 50 m in width (0.5 ha). Along the 100 m transect downstream, N_2O emission and soil sampling were taken at 18.5 m intervals with random horizontal locations in maize areas. Initial and validating data such as N_2O flux and environmental parameters were measured at each of these spot samples (*n*=22) monthly from May 2009 to April 2010.

6.2.2 Initial data

Initial data were required for the simulation of N_2O emission by DNDC model of each sites consisting of three categories;

Average maximum and minimum daily temperature of 2009 were 36.3 and 19.5 °C, respectively. Rainfall accumulation of 2009-2010 was 1,095.3 mm. Climatic data was obtained from one weather station in Nan Province and it was no scientifically different statistics between sites. Climatic data all daily maximum and minimum temperatures and rainfall were collected at Nan weather station far away from study sites about 15 km. Also relative humidity, soil temperature at 50 mm depth and air temperature were measured on site in the same period of gas flux collection during 9.30-11.00 am (Table 6.1).

Soil N_2O flux of each sampling location in maize area was collected by close chamber method (Rochette and Eriksen-Hamel, 2008). Then the amount of N_2O in vials was determined by μECD detector of Gas Chromatography (GC) configured with a 15 m × 0.53 mm PLOT GS-Q column. The conditions of GC were 40°C column temperature; 50°C injector temperature; ratio pulsed split mode at 5:1; 300°C detector temperature; 5.5 ml min^{-1} N_2 carrier gas. The rate of N_2O emission was calculated by the increasing of N_2O concentration in vials overtime at 0, 10, 20, and 30 min.

Intact soil core with diameter 5 cm high and 5.45 cm were collected 3 replicate batches near each sampling location and dried at 105°C for 72 hour and calculated porosity and WFPS by the method of Blake (1965).

To study soil characteristics, soil samples were collected by soil auger at 5 cm depth. Fresh soils were extracted as soil solution with 0.5 M K_2SO_4 (Jones and Willett, 2006) to determine net nitrification, NH_4^+ and NO_3^- according to the protocol of Robertson et al. (1999), Mulvaney (1996), Miranda et al. (2001), respectively. DOC soluble extraction was determined by dry combustion (Analytic Jena, model 3100 C/N). The remained soil samples were dried and sieved at < 2mm and <500 μm to determine soil texture, soil pH, total soil C by the hydrometer method of Sheldrick and Wang (1993), pH meter, and TruSpec® CN analyser (Leco Corp, St Joseph, MI), respectively.

Therefore, overall soil characteristics at tropical riparian specific site was systematized as a silt loam with 20-21% clay, pH at 6.11-6.36, soil carbon 0.0143-0.0157 kg C kg^{-1}, 3.88-3.94 NH_4^+ mg N kg-^{1}, 8.66-12.47 NO_3^- mg N kg-^{1}, 49-51% porosity, and 34-42% WFPS (Table 6.1).

For framing production and management, maize was double cultivated on May, 17th 2009 and September, 15th 2009 and harvested on August, 15th 2009 and February, 1st 2010, respectively. The maize production was 3,100-3,480 yield biomass kg C ha^{-2} and 48.2 % crop residual fraction. The tillage was done 2 times per crop by ploughing with molboard at 20 cm depth on April, 21st, and September, 1st 2009 and poloughing sightly again at 5 cm depth on May, 7th and September, 14th 2009, respectively. The maize cultivation applied intensively inorganic nitrogen fertilizer. Inorganic N fertilizer formula, either 16-20-0, 15-15-15, or 46-0-0, was applied twice at the rate of about 175 kg N ha^{-1} year^{-1}: firstly, during maize sowing on May, 7th and September, 15th 2009 at 30 kg N ha^{-1}, secondly, either15-30 days after seeding or after weed elimination on May, 21st 2009 and September, 25th 2009 at 57.5 kg N ha^{-1}.

Table 6.1 Initial data input to DNDC model.

Parameters	Study site 1 (n=8)	Study site 2 (n=7)	Study site 3 (n=7)
1. Climate data			
Latitude (degree)	18º37’ N	18º35’ N	18º33’ N
Maximum of average daily temperature of 2009 (°C)	33.6	33.6	33.6
Minimum of average daily temperature of 2009 (°C)	19.5	19.5	19.5
Yearly accumulated rainfall of 2009 (mm)	1,095.3	1,095.3	1,095.3
N concentration in rainfall (mg N l^{-1})	0.53	0.53	0.53
Atmospheric NH$_3$ concentrations (µg N m^{-3})	0.06	0.06	0.06
Atmospheric CO$_2$ concentrations (ppm)	350	350	350
2. Soil properties (0–5 cm depth)			
Vegetation type	Maize	Maize	Maize
Soil texture*	Silt loam	Silt loam	Silt loam
Bulk density* (g cm^{-3})	1.35 ± 0.11^{B}	1.33 ± 0.10^{B}	1.30 ± 0.11^{A}
Clay fraction* (0-1)	0.20 ± 0.02^{A}	0.21 ± 0.005^{B}	0.21 ± 0.01^{B}
Soil pH*	6.12 ± 0.20^{A}	6.11 ± 0.22^{A}	6.36 ± 0.23^{B}
Initial C content at surface soil* (kg C kg^{-1})	0.0145 ± 0.014^{A}	0.0143 ± 0.001^{A}	0.0157 ± 0.001^{B}
NH$_4^+$ *(mg N kg-^{1})	3.94 ± 1.99^{A}	3.88 ± 2.17^{A}	3.88 ± 1.98^{A}
NO$_3^-$ *(mg N kg-^{1})	8.66 ± 7.23^{A}	12.47 ± 10.83^{B}	9.66 ± 7.53^{A}
Porosity* (0-1)	0.49 ± 0.04^{A}	0.50 ± 0.04^{A}	0.51 ± 0.04^{B}
WFPS* (0-1)	0.35 ± 0.22^{A}	0.34 ± 0.24^{A}	0.42 ± 0.22^{B}
Depth of water-retention layer (cm)	100	100	100
Slope (%)	2	2	1
3. Farming management			
Maximum biomass of gain (kg C ha^{-2})	3100.0	3291.0	3480
Maximum biomass of leaf and stem (kg C ha^{-2})	3100.0	3291.0	3480
Maximum biomass of root (kg C ha^{-2})	1145.9	1216.6	1286.45
Biomass fraction of gain (0-1)	0.156	0.156	0.156
Biomass fraction leaf and stem (0-1)	0.156	0.156	0.156
Biomass fraction root (0-1)	0.422	0.422	0.422

The values presented are mean and standard deviation (SD) The superscript capital letters indicate that mean variation and homogeneous subset according to Dancan’ post-hoc test are significantly different of each study sites ($P<0.05$).

6.2.3 DNDC model, validating data, and model evaluation

In this study the DNDC model V9.2 was tested on 3 replicates of each study sites. All initial data of climate, soil, and maize framing production and management were input into the model. N_2O emission, NH_4^+, NO_3, WFPS, and soil temperature simulation were validated with those from field data at the date of observation. The methods applied to test the goodness-of-fit between simulated values (Xi) and observed values (Yi) were following Smith, et al. (1997) and Chirinda (2011) that are;

The model efficiency (ME) is the ratio of the efficiency of the DNDC model to the efficiency of the observed data minus by the mean of the observations (Equation 1).

$$ME = 1 - \frac{\sum (Xi - Yi)^2}{\sum (Yi - \overline{Y})^2} \quad -\infty \leq ME \leq 1 \qquad (1)$$

ME values can be in between negative ∞ and 1. ME value toward 1 indicates high model efficiency that measured data is better than the mean of the observations.

The coefficient of determination (r^2) is the total variance of the observed data to the predicted data. If the coefficient of determination is toward 1, it indicates that simulated values are in positive relation to observed values (Equation 2).

$$r^2 = \frac{\left(\sum (Xi - \overline{X})(Yi - \overline{Y})\right)^2}{\sum (Xi - \overline{X})^2 \otimes \sum (Xi - \overline{X})^2} \quad 0 \leq r^2 \leq 1 \qquad (2)$$

The normalized root mean square prediction error ($RMSPE_n$) shows the model precision when the value is toward zero, which is inverse to the coefficient of determination (Equation 3).

$$RMSPE_n = \frac{\sqrt{\frac{\sum (Xi - Xi)^2}{n}}}{SD} \tag{3}$$

The mean bias (*MB)* is used to determine model accuracy by means of the deviations between observed and simulated values (Equation 4). If *MB* is less than zero, it presents that the chosen model overestimates. In contrast, if it is more than zero, it presents that the chosen model underestimates.

$$MB = \frac{\sum_{i=1}^{n} (Yi - Xi)}{n} \tag{4}$$

The relative deviation (*RD*) is shown the percentage of deviation of differences between simulated and observed values (Equation 5). The less deviation percentage indicates that.simulated values are fitted to observed values and the power of modeller used for prediction is satisfactory.

$$RD = \frac{(Xi - Yi)}{Yi} \times 100 \tag{5}$$

6.2.4 Sensitivity analysis

Model sensitivity of variation to N_2O emission was tested by individual either increases or decreases of major controlling factors (*P*); 25% soil carbon, 30% daily rainfall, and 175 and 272.5 kg N ha^{-1} $year^{-1}$ applied fertilizer. Model sensitivity was evaluated as a variation of simulated N_2O flux to increase or decrease of an initial input data of *P* following equation 6;

$$\beta = \frac{N_2O^1 - N_2O^0}{N_2O^0} \Big/ \frac{P^1 - P^0}{P^0} \tag{6}$$

Where N_2O^1, N_2O^0, P^1 and P^0 are increase and decrease of N_2O emission and *P* value simulated from input initial data by DNDC model, respectively. N_2O flux sensitivity due to the changing of *C* is presented by the standardized coefficients value (β); the intersection of N_2O flux as *P* value is zero. The sign of β can be also indicated the negative or positive correlation (Kiese et al., 2011).

6.3 Results and discussions

6.3.1 N_2O flux, NO_3^-, WFPS, and Soil temperature simulation

Annual, wet and dry seasons of N_2O flux, NO_3^-, WFPS, and soil temperature simulated by DNDC model were lower than those of observed data at tropical riparian ecosystem along the Nan River, Northern Thailand for May 2009 - April 2010 (Figures 6.1-6.8). Model efficiency for annual, wet and dry season; N_2O flux were -2.11, -3.02, and -1.78, respectively, indicating that the mean of the observed values was a higher than the model-estimated values. For model precision, R^2 (0.005) was remarkable low. It was presented the weak correlation mean value between N_2O flux modeled and field measurement. $RMSPE_n$, inverse R^2 negative model precision, showed that the residual values of model prediction was high. For model accuracy, *MB* and *RD*, the different means and deviations between N_2O flux by observed and simulated values, reflected that the DNDC model was underestimated (Table 6.2).

In the wet season, the impulses of N_2O emissions occurred in early wet season due to wet soil by the rain after prolonged soil dryness in dry season and input fertilizer in April-May 2009, leading to largest magnitude of N_2O emissions. This is relavent to the effect of rewetting to N_2O emssion in field experiment study of Byrnes et al., (1993); Davidson et al., (1993); Dobbie et al., (1999); Garcia-Montiel et al., (2003); Butterbach-Bahl et al., (2004); Van Haren et al., (2005); and Werner et al., (2006).

N_2O flux simulated from riparian soil was likely not emitted through dry season except January 2009 that had rainfall. This induces the pulse peak of N_2O flux due to increase soil water content in short period in dry season. N_2O emissions were higher in soils due to soil redox potential (Eh) of rewetting events in maize field in a narrow reducing condition range 420-575 mV (Hernandez-Ramirez et al., 2009). In this study, N_2O emission was started at Eh 535.3 mv when received rainfall >13 mm per day.

It is possible that the monthly observed data used for validating simulated data is rough scale. It is not sufficient to detect the rapid nitrogen transformation. Observed data at fine temporal scale may be useful to increase the goodness-of-fit between simulated and observed values in term of the concurrent of the accuracy of the emission date. However, DNDC is the process-based model that continuously simulates C and N biogeochemistry of each time step. If the initial data is correct, especially farming management such as input fertilizer timing, the data of observed data and simulated output is the same time. Therefore, any time scale of observation data is capable to validate model.

The DNDC capability to simulate WFPS compared with observed data was fitted but lower estimated in wet season and over estimated in dry season. WFPS is critical to determine N_2O flux after fertilizer has been applied (Abdalla, et al., 2009). Increasing WFPS up to 60% can be reduced contribution of N_2O formation by nitrifying bacteria and increased N_2O production by denitrifying bacteria (Bateman and Baggs, 2005).

Although N_2O emissions are strongly related to soil NO_3^- concentrations (Groffman et al., 2000; Hefting, 2003; Vilain et al., 2010), the correlation of both observed and modelled values to applied N fertilizer was explicated only early wet in May 2009 and mid wet season in September. The NO_3^- prediction from DNDC model responded only to N fertilizer input and the concentration was not more than 0.05-8.6 N ka yr^{-1}, while NO_3^- from field observation ranged 12.49-17.39 N ka yr^{-1}. It was likely that during the end of wet season and all dry season, moisture content and nitrate were low; DNDC model assumed soil condition was not suitable for N_2O formation both denitrification and nitrification.

The simulated soil temperature was very fit goodness with observed data which was indicated by the 0.45 annual *ME* and -2.10 %*RD*. The N_2O emission was positively associated with the increasing soil temperature.

Table 6.2 Average and standard deviation of observed value and modeled values and their model evaluation parameters.

Parameter	Observed value	Modeled value	Model evaluation parameters				
			ME	*RMSPEn*	R^2	*MB*	*%RD*
N_2O flux $^{\S,\$,¥}$ (kg N ha^{-1} yr^{-1})							
Annual	2.20±1.2	1.07±0.8	-2.11	0.190	0.005	0.10	-40.17
Wet season$^{\#,¢}$	1.33±0.7	0.86±0.7	-3.02	0.212	0.006	0.08	-14.67
Dry season	0.87±0.6	0.21±0.1	-1.78	0.165	0.001	0.12	-66.07
Average NO_3^- $^{\S,\$,¥}$ (kg N ha^{-1})							
Annual	14.96±12.7	4.29±11.8	-1.27	19.092	0.027	10.66	-62.65
Wet season$^{\#,¢}$	12.49±10.6	8.60±15.7	-0.94	15.327	0.174	3.88	-25.09
Dry season	17.39±13.9	0.05±0.05	-1.56	22.184	0.177	17.34	-99.64
Average WFPS $^{\S,\$,¥}$ (0-1)							
Annual	0.37±0.23	0.31±0.07	0.17	0.205	0.307	0.06	25.37
Wet season$^{\#,¢}$	0.54±0.18	0.35±0.07	-0.93	0.248	0.231	0.19	-28.79
Dry season	0.20±0.11	0.26±0.06	-2.65	0.341	0.060	0.28	83.07
Average soil temperature (°C)							
Annual	28.29±3.62	27.31±2.57	0.45	2.687	0.522	0.98	-2.70
Wet season$^{\#,¢}$	30.05±2.18	28.28±1.19	-0.41	2.580	0.252	1.76	-5.52
Dry season	26.54±3.92	26.34±3.15	0.49	5.278	0.502	3.71	0.13

The # and ¢ indicate significantly different of mean between wet and dry seasons within observed values and modelled values at $P<0.05$. The §, \$, and ¥ present significantly different between mean of observed values and modelled values categorized by annual, wet and dry season at $P<0.05$.

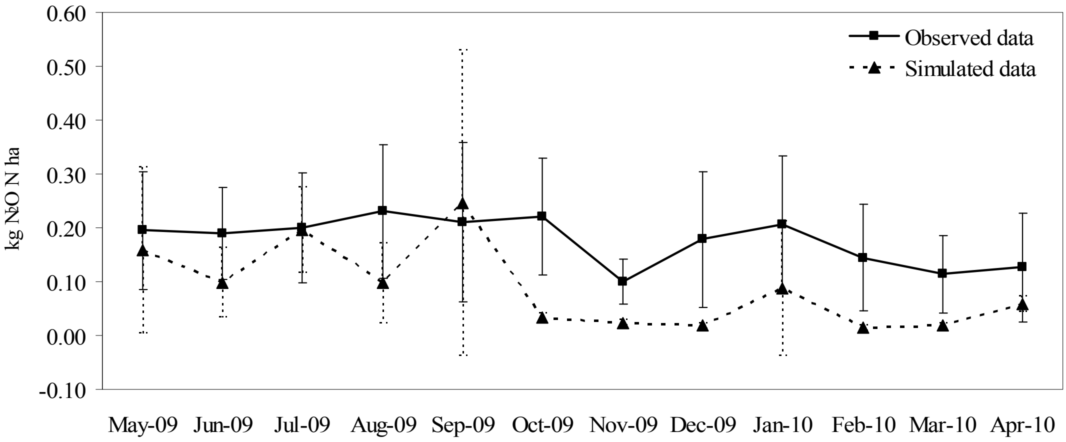


Figure 6.1 Average and standard deviation of N_2O emission from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

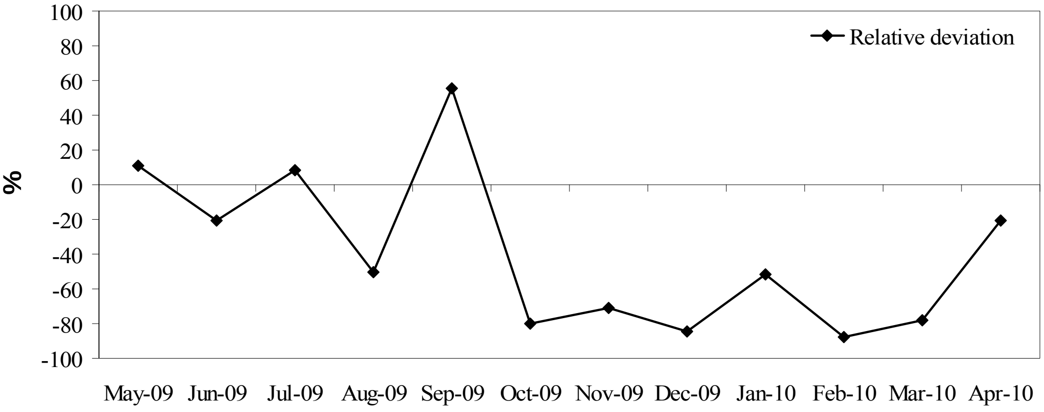


Figure 6.2 Relative deviation of N_2O emission from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

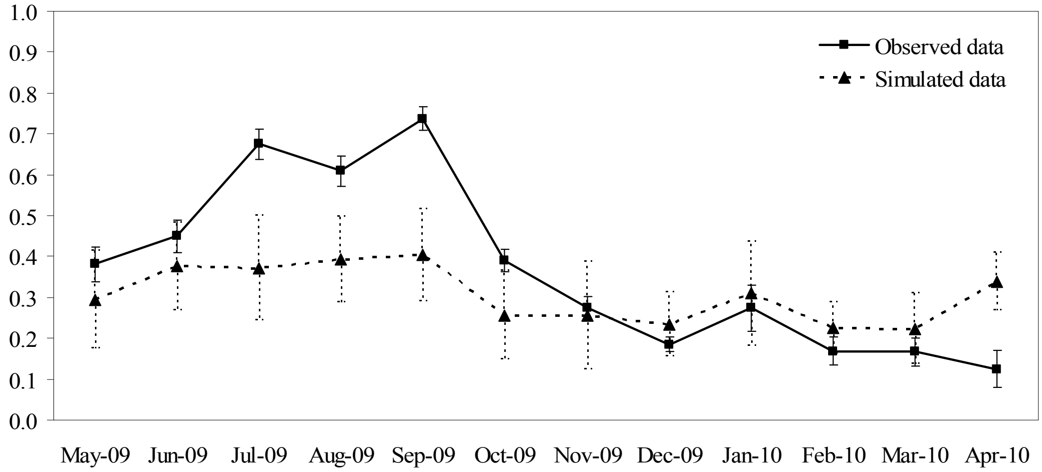


Figure 6.3 Average and standard deviation of WFPS from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

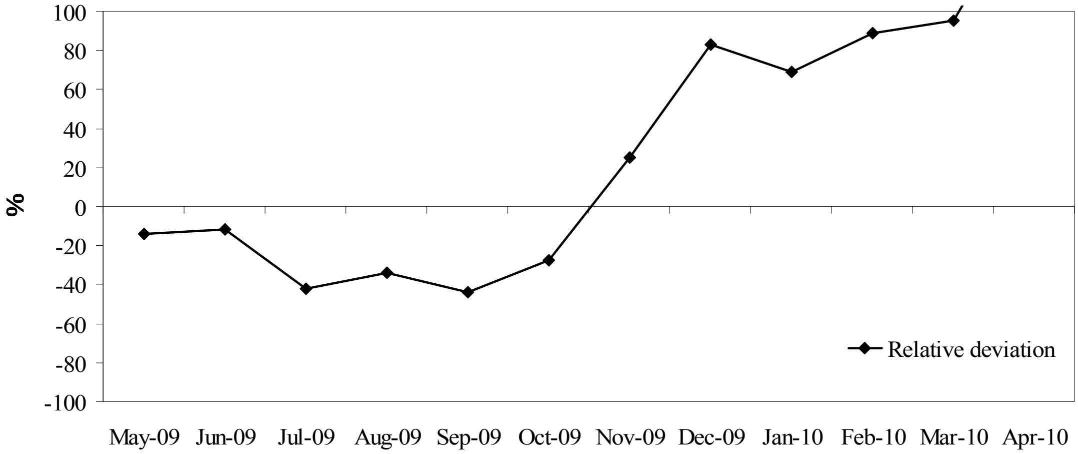


Figure 6.4 Relative deviation of WFPS from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

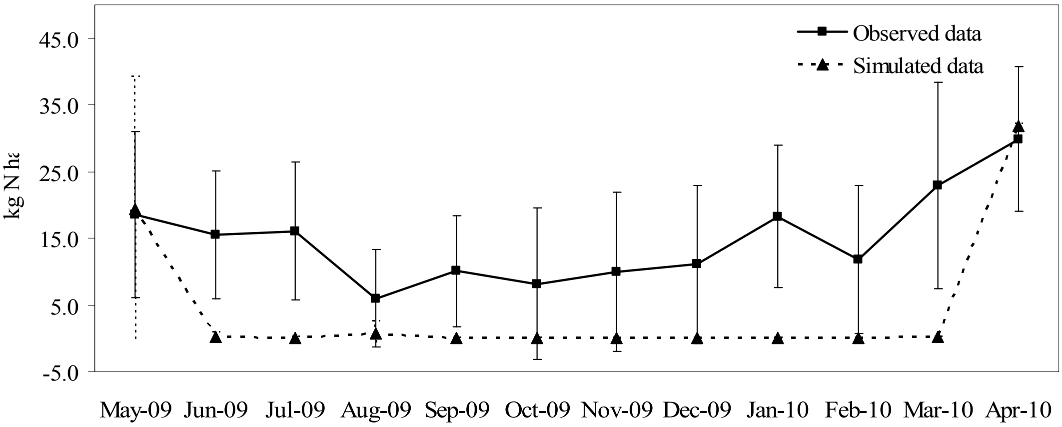


Figure 6.5 Average and standard deviation of nitrate from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

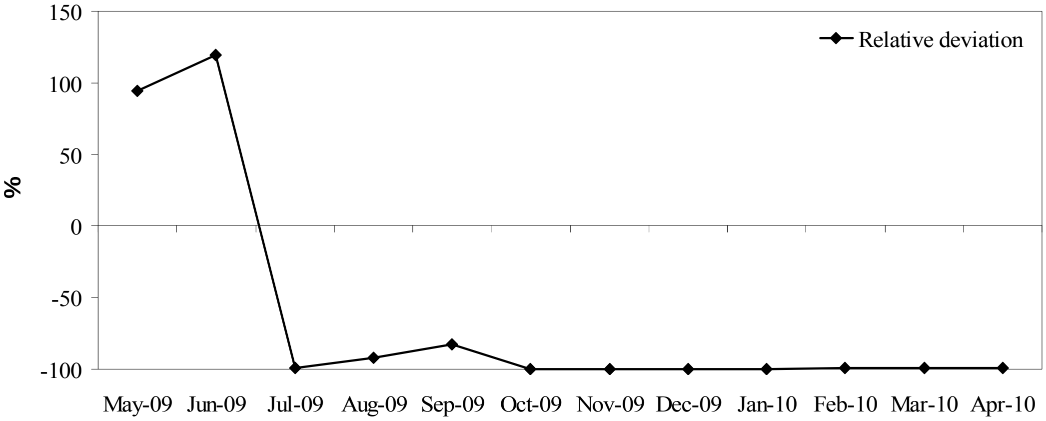


Figure 6.6 Relative deviation of nitrate from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

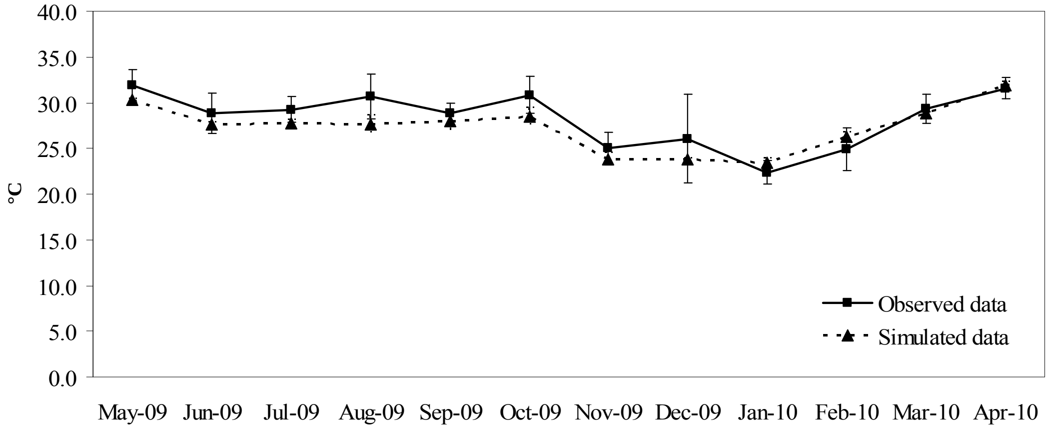


Figure 6.7 Average and standard deviation of soil temperature from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

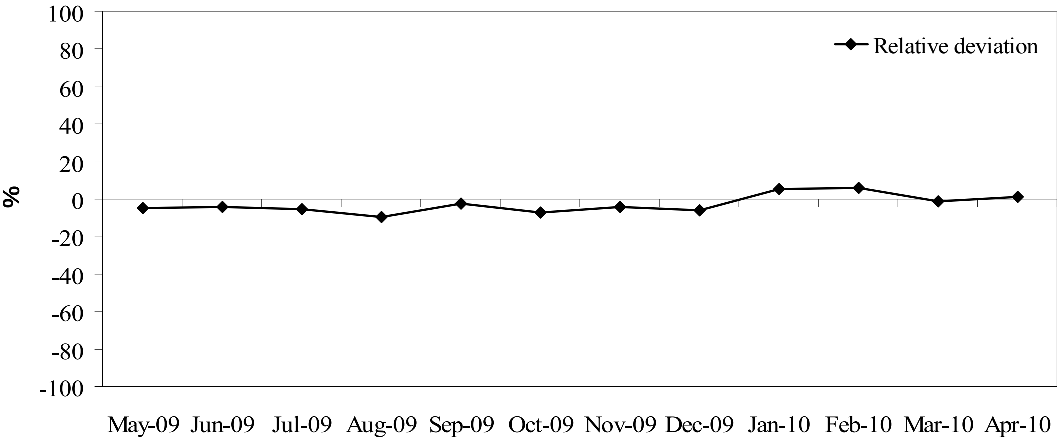


Figure 6.8 Relative deviation of soil temperature from maize field in wet (May - Oct 09) and dry season (Nov 09 - Apr 10).

6.3.2 Sensitivity analysis

Both simulation and observation incicated increased or decreased soil carbon, daily rainfall, and N input, N_2O emissions. The standardized coefficients (β) indicated that annual N_2O emission was sensitized by soil carbon (β=1.42), WFPS (β=0.53), and inorganic nitrogen (β=0.26). Regarding partially sensitized controlling factors in wet and dry seasons, standardized coefficients (β) of soil carbon, WFPS and inorganic nitrogen were 2.63-0.36, 1.12-0.40, and 0.26-0.24, respectively (Table 6.3).

Table 6.3 Sensitivity analysis

Parameter	N_2O flux (kg N ha^{-1})						Standardized coefficients (β)		
	Annual	%	Wet season	%	Dry season	%	Annual	Wet season	Dry season
Baseline	1.07		0.86		0.21				
Soil carbon									
+25%	1.556	45	1.533	43	0.023	2	1.42	2.63	0.36
-25%	0.807	25	0.802	25	0.005	0			
Daily rainfall									
+30%	1.297	21	1.285	20	0.012	1	0.53	1.12	0.40
-30%	0.920	14	0.919	14	0.001	0			
Applied fertilizer									
+30% (227.5 kg N ha^{-1})	1.26	17	1.25	17	0.01	0	0.26	0.26	0.24
-30% (122.5 kg N ha^{-1})	0.76	29	0.75	30	0.01	0			

N input was not enhanced N_2O emission due to limited soil carbon in conventional maize cultivation and rainfall. The farmers were lacking input organic matter and long term chemical fertilizer; therefore, when simulated N_2O by increased soil carbon, N_2O emission is high production. Organic matter served as carbon source to formation by nitrifying and denitrifying bacteria, and electron donor to completed denitrification. When the soil is in more reduced, electrons are sufficient. Then, denitrification tends to complete N_2O reduction to N_2 as the end product due to the competition between reduced N_2O and nitrate (Firestone et al., 1980).

WFPS controlled by rainfall was the moderate sensitivity (β=0.53) to N_2O emission. The percentage of increasing or decreasing N2O emission due to WFPS took place during wet season about 14% and 20%, because rainfall and rainfall accumulation in soil pore induces high water content in soil pore.

Interestingly, increasing N input contributes less percentage of N_2O emission than those of increasing soil carbon and WFPS. In fact, the predicting N_2O fluxes was sensitivity at high inputs of N fertilizer about 140 kg N ha^{-1} and sensitivity is low at zero or low N input treatments (0–70 kg N ha^{-1}) (Abdalla, et al., 2009). This is in contrast to this study. When the farmers applied N fertilizer to maize field, N_2O emission increased about 17%. It is indicated that, although nitrogen is abundant, the N_2O emission is less than expecting due to the lack of soil carbon and WFPS.

6.4 Conclusions

This study presented the testing of DNDC model which has been developed for agricultural system in temperate zone for simulating N_2O emission validated with N_2O emission from field observation. When this model was applied with the field data to maize agricultural area in tropical riparian zone, Nan province, Thailand, The accuracy of model indicates the underestimation of N_2O flux from maize field. It is clear that the model precision is remarkably low. DNDC model's sensitivity particularly indicated low values in term of the amount of soil carbon content, WFPS except for N input. In field observation, although WFPS is low level in soil, the N_2O is still emitted. This indicates that nitrifying and denitrifying bacteria activities in DNDC model are limited to the initial low WFPS, and soil carbon in this study, tropical riparian zone. It is clear that the performance of model calibration for anaerobic balloon factors before simulated N_2O emission in tropical riparian zone must be considered. The results indicate that fine temporal scale at daily or weekly N_2O flux observation may be needed to validate for the precision and accuracy of DNDC model between observed data and simulated N_2O emission from tropical ecosystem.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

This research demonstrated the variability of N_2O emission from tropical riparian ecosystems particularly in the Nan River, Northern Thailand, which is removed excess nitrogen nutrients discharged from groundwater and runoff before drained to river ecosystem. Apparently, it is suspected as important N_2O flux sources because it is swapping pollution from NO_3^- to N_2O as crucial greenhouse gases by denitrification. Moreover, the high level of organic carbon from flooding every year and WFPS influenced from river may enhance N_2O production and emission. The study composed of three main parts: 1) the seasonal and spatial variability of N_2O emissions and their associated with soil properties and environmental conditions; 2) the trend of N_2O emission and controlling factors on distal proximity of sampling location from river and landscape arrangement of land use types; and 3) estimation and sensitivity of N_2O flux by DNDC, process based model. These objectives of the study are already proved the list of research question in the following:

7.1.1 Seasonal N_2O emission in different land uses

N_2O emission variability was implied the effect of spatiotemporal of land use types and seasons. The seasonal N_2O flux was compared between wet and dry seasons, while the different land use in variation of N_2O emission was defined in different land uses between leguminous reforestations, solely *Samanea saman* (Jacq.) Merr as nitrogen fixation tree and conventional maize (*Zea mays* L.) agriculture with intensively applied nitrogen fertilizer. Flux of N_2O measured by closed chamber during May 2009-April 2010 showed different land uses and season as main effect and their interaction made N_2O flux variation. Both wet and dry seasons, N_2O flux from reforestation was higher than that from agricultural area with maize. When the study compared mean N_2O flux in different seasons, the wet season was greater N_2O flux than dry season. Water filled pore space was the main controlling factor to N_2O

formation and emission, though soil carbon and available nitrate were higher than the threshold of nitrifying and denitrifying bacteria’s requirement. Interestingly, N input in maize area was higher than reforestation area for 3-4 times, but it influenced N_2O emission only early wet season and lower N_2O emission than reforestation. It was explained that the stable temperature and high soil moisture under canopy of reforestation both wet and dry seasons were likely to facilitate N mineralization as the first step of N transformation. At maize area, the high rate of N fertilizer may mainly be absorbed by plant uptake, ammonia volatilization, leaching via ground water and runoff. Denitrification was partially removed nitrate and then emitted low N_2O. Moreover, different soil physical structure in relation to different land uses was accounted for N_2O emitted. High bulk density was induced N_2O emission by reducing oxygen diffusion and water flow in soil pore, thus increasing anaerobic micro sites and accelerating denitrification. It is indicated that tillage practice has often produced high soil compaction then become controlling factor for N_2O emission.

7.1.2 Proximate of Seasonal N_2O emission across lateral transfer

The means of N_2O emission have high deviation not only among different land use types but also spatial heterogeneity in terms of lateral flow in riparian zone. This study was conducted the measurement of N_2O emission and soil properties as increase distal proximity of sampling location from River and landscape arrangement of two land use types in which reforestation was located close to River and adjacent with agricultural area with maize. Although the trend at reforestation and agricultural area with maize was not significantly different due to spatial homogeneity along lateral flow, the mixed land uses indicated the inversion of N_2O flux with decreased distance from river. Apparently, the effect of spatial heterogeneity on N_2O emission at lateral flow across tropical riparian was not clear because the variation of N_2O emission was as a result of either gradually change of WFPS and nitrate concentration in lateral transfer itself or different land uses. The additional experimental treatment of land use arrangement between agricultural areas located near river adjacent with reforestation should be useful as reference of the effect against with pervious experiment. This study sites are located at the upper river basin where river water level is high, shallow groundwater is beneath root zone. The nitrate concentration was skipped. Then other N transformation of nitrate removal form plant assimilation is not observed. Therefore, the ecological systematic approach is required for elucidating the whole of N transformation movement of mass balance of input-processes-output in riparian zone. However, the proportion of N transformation is not easily investigated, and the causing loop of feedback correlated to those mechanisms in system is complex.

7.1.3 Simulated N_2O emission by process-based model

The DNDC model used to simulate N_2O emission showed that the model accuracy was not acceptable to simulate N_2O flux from agricultural soil in tropical riparian ecosystem when validated with monthly interval N_2O flux observation. However, the simulation N_2O emission and soil parameters in dry season by DNDC model was not concurred with observed values at field experiment. It is clear that the model must be calibration properly by using functional of N transformation and soil properties of tropical zone. However, the rational factors of ecological functions in tropical riparian ecosystem are still lacking and difficult to study in field experiments because of the complex of the interaction between biotic and abiotic components.

7.1.4 Comparison of N_2O flux from different ecosystems

Tropical soil contributed N_2O global budget is concerned due to high productivity from forest soil. Annual N_2O emission from the tropical riparian reforestation was similar to that reported from temperate riparian forests and other ecosystems. Interestingly, agricultural area with maize as the source of N_2O flux is comparable to other crops cultivated in riparian ecosystems, but it is higher than those of other N_2O fluxes from crops grown with applied fertilizer in terrestrial zones. The mitigation N_2O emission from agro ecosystem in tropical riparian zone should draw attention to the adequate fertilizer application to enhance nitrogen use efficiency and then decrease N_2O emission. In this study, ecological service for detoxification from nitrate removal as the source of N_2O emission has been not presented and it compromises their other aspects of ecosystem services. However, the net effect of riparian zone contributed N_2O flux to atmosphere needs to be understood so that the mitigating of greenhouse gas can be implemented effectively.

7.1.5 Direct N_2O emission factor

This study proposed the direct emission factors from cultivated maize with intensive input nitrogen from crop residual and leguminous reforestation are 0.01 kg N_2O–N (kg N input)$^{-1}$ and 0.06 kg N_2O–N (kg N input)$^{-1}$, respectively. EF of maize cropland is relevant to emission factor of input synthesized fertilizer introduced by IPCC. The calculated emission factor of leguminous reforestation is lower than the biological fixation in cropland proposed by IPCC.

7.2 Recommendations

N_2O emission from agricultural activity in riparian wetland as the source of emission is controversial. This research proposed the alternative scientific data of N_2O emission in riparian ecosystem for use as basic knowledge to deal with the N_2O emission management and mitigation from agriculture area located in riparian zone in the following:

7.2.1 Swapping pollution

Swapping pollution from nitrate reduction to nitrous oxide in agricultural area with maize applied nitrogen fertilizer is small proportion. To increase ability of ecological function of detoxification to the nitrogen in riparian zone should play attention to establish tree or grass buffer strip. Most agricultural types along the Nan River are were classified as crop applied fertilizers with no buffer strip. Nitrate and sediment may be directly carried to river by groundwater and runoff. Grass and tree buffer strips with 10-30 m is enough to retain and intercept nutrient and soil erosion.

However, the study of nitrate reaching and runoff and the ability of riparian buffer strip in Thailand are required. It is useful to determine the size of buffer strip. Moreover, the rate of N transformation is also useful to calculate the indirect N_2O emission from nitrate reaching and runoff.

7.2.2 Mitigation of N_2O emission at specific site

At specific site scale, nitrogen fertilizer applied in maize plot is a source of N_2O emission. Split and timing of fertilizer is helpful to delay nitrogen transformation of NO_3^- and N_2O flux, thus increasing nitrogen assimilation by crop. The result shows that area where closed distance to river have higher rate of N_2O emission than upper area. On the other hand, inorganic nitrogen has lower concentration at river edge than upper area. This is evident to selected location to applied fertilizer rate to maximum nitrogen use efficiency and reduces N_2O emission. It is recommend that farmer should be reduced the rate of applied fertilizer because this position is received nitrogen and sediment that drained lateral transfer from upper zone.

However, in this study proposed only heterogeneity of reforestation closed to river adjacent with maize area, but not established inverse heterogeneity of that arrangement to compare the effect of N^2O emission as a consequence of whether lateral transfer in landscape heterogeneity or different land uses. Moreover, to improve the accuracy of mitigating N_2O emission and N transformation across lateral transfer, it is should be set the experimental design for other landscape arrangements or land use types.

7.2.3 Estimation of N_2O emission at regional scale

In Thailand, maize was cultivated 1,097,825 ha in 2004. This study estimate the national N_2O emission from maize area with applying input fertilizer minus with 10% NH_3 + NOx loss at 230.4 kg N ha^{-1} yr^{-1}. Then, total N_2O emission is 2,024 ton N_2O-N yr^{-1} with range 1,771-2,529 ton N_2O-N yr^{-1}. However, such estimation is rough due to lack of accuracy and precision of nitrogen input from residual and chemical fertilizer. Moreover, the EF for calculating N_2O emission comes from monthly scale of N_2O flux observation and dose not have control treatment (no applied fertilizer). Therefore, using this EF may be inaccuracy and high variation. The study of N_2O emission at fine scale; daily or weekly will help the inventory N_2O emission of Thailand better reliability.

7.2.4 Using the systematic relationship parameters and data

This study applies soil data, environmental conditions, and farming practices to simulate N_2O emission and other C and N pool by DNDC model. It is possible use the systematic C and N parameters to study the other aspect of ecological service and function and environmental management such as Life Cycle Assessment (LCA), ecological modeling, pollution modeling, and other process based model or agent based model. It is noted that these parameters must be collected in tropical riparian ecosystem. Therefore, the models have to be calibrated by the set of factor or function that represent tropical characteristic. However, there are a few studies on N and C biogeochemistry function in tropical zone. It is recommended that the study of cause and feedback loop among biotic and abiotic components contributed to N_2O formation and emission will provide some constant factors with more validated in the equation of calibration model step.

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APPENDICES

Appendix 1 Reforestation stand properties

Study site	Tree numbers	Circumstance (cm)	DBH (cm)	DBH^2	Basal area (m^2)	Total basal area (m^2)	Basal area (m^2 ha^{-2})
Site 1							
Reforestation	1	103.0	32.8	1,074.9	0.1	2.6	8.8
(Sampling	2	112.0	35.7	1,271.0	0.1		
area is 0.3 ha)	3	112.0	35.7	1,271.0	0.1		
	4	86.0	27.4	749.4	0.1		
	5	96.0	30.6	933.8	0.1		
	6	67.9	21.6	467.6	0.0		
	7	33.0	10.5	110.3	0.0		
	8	154.0	49.0	2,402.9	0.2		
	9	165.0	52.5	2,758.5	0.2		
	10	101.7	32.4	1,048.6	0.1		
	11	122.7	39.1	1,525.4	0.1		
	12	154.0	49.0	2,402.9	0.2		
	13	107.3	34.1	1,165.4	0.1		
	14	116.0	36.9	1,363.4	0.1		
	15	102.0	32.5	1,054.1	0.1		
	16	147.5	47.0	2,204.4	0.2		
	17	136.0	43.3	1,874.0	0.1		
	18	45.5	14.5	209.8	0.0		
	19	66.5	21.2	448.1	0.0		
	20	159.0	50.6	2,561.5	0.2		
	21	133.0	42.3	1,792.3	0.1		
	22	70.5	22.4	503.6	0.0		
	23	102.5	32.6	1,064.5	0.1		
	24	82.5	26.3	689.6	0.1		
	25	92.8	29.5	871.6	0.1		
	26	113.8	36.2	1,312.1	0.1		
	27	60.0	19.1	364.8	0.0		
Mixed land use	1	176.0	56.0	3,138.5	0.2	3.3	12.5
(Sampling	2	124.4	39.6	1,568.0	0.1		
area is 0.3 ha)	3	123.0	39.2	1,532.9	0.1		
	4	154.0	49.0	2,402.9	0.2		
	5	140.0	44.6	1,985.9	0.2		
	6	32.0	10.2	103.8	0.0		
	7	250.0	79.6	6,332.5	0.5		
	8	156.4	49.8	2,478.4	0.2		
	9	181.0	57.6	3,319.4	0.3		
	10	216.0	68.8	4,727.2	0.4		
	11	154.0	49.0	2,402.9	0.2		
	12	155.0	49.3	2,434.2	0.2		
	13	194.0	61.8	3,813.3	0.3		
	14	161.2	51.3	2,632.9	0.2		
	15	161.0	51.2	2,626.3	0.2		
Site2							
Reforestation	1	295.4	94.0	8,841.4	0.7	5.4	14.0
(Sampling	2	150.0	47.7	2,279.7	0.2		
area is 0.4 ha)	3	137.0	43.6	1,901.7	0.1		

Study site	Tree numbers	Circumstance (cm)	DBH (cm)	DBH^2	Basal area (m^2)	Total basal area (m^2)	Basal area (m^2 ha^{-2})
	4	168.0	53.5	2,859.7	0.2		
	5	305.0	97.1	9,425.4	0.7		
	6	197.0	62.7	3,932.2	0.3		
	7	280.0	89.1	7,943.5	0.6		
	8	197.3	62.8	3,944.1	0.3		
	9	140.0	44.6	1,985.9	0.2		
	10	168.0	53.5	2,859.7	0.2		
	11	231.0	73.5	5,406.6	0.4		
	12	74.4	23.7	560.8	0.0		
	13	80.0	25.5	648.5	0.1		
	14	75.5	24.0	577.6	0.0		
	15	188.0	59.8	3,581.1	0.3		
	16	135.0	43.0	1,846.6	0.1		
	17	149.0	47.4	2,249.4	0.2		
	18	115.0	36.6	1,340.0	0.1		
	19	163.0	51.9	2,692.0	0.2		
	20	148.8	47.4	2,243.4	0.2		
	21	139.0	44.2	1,957.6	0.2		
Mixed land use	1	129.0	41.1	1,686.1	0.1	4.0	8.6
(Sampling	2	104.8	33.4	1,112.8	0.1		
area is 0.5 ha)	3	187.7	59.7	3,569.7	0.3		
	4	239.0	76.1	5,787.5	0.5		
	5	180.4	57.4	3,297.4	0.3		
	6	120.9	38.5	1,481.8	0.1		
	7	180.8	57.6	3,312.0	0.3		
	8	122.0	38.8	1,508.1	0.1		
	9	238.4	75.9	5,758.5	0.5		
	10	199.0	63.3	4,012.4	0.3		
	11	226.0	71.9	5,175.1	0.4		
	12	217.0	69.1	4,771.1	0.4		
	13	155.5	49.5	2,450.0	0.2		
	14	203.0	64.6	4,175.3	0.3		
	15	160.7	51.2	2,616.6	0.2		
Site 3							
Reforestation	1	157.5	50.1	2,513.4	0.2	6.4	16.1
(Sampling	2	154.7	49.2	2,423.8	0.2		
area is 0.4 ha)	3	146.0	46.5	2,159.8	0.2		
	4	128.0	40.7	1,660.0	0.1		
	5	291.0	92.6	8,579.9	0.7		
	6	177.0	56.3	3,174.3	0.2		
	7	128.8	41.0	1,679.5	0.1		
	8	170.0	54.1	2,928.2	0.2		
	9	199.7	63.6	4,039.3	0.3		
	10	136.3	43.4	1,880.9	0.1		
	11	81.0	25.8	664.8	0.1		
	12	196.0	62.4	3,892.3	0.3		
	13	156.0	49.7	2,465.7	0.2		
	14	166.0	52.8	2,792.0	0.2		
	15	191.0	60.8	3,696.3	0.3		
	16	133.0	42.3	1,792.3	0.1		

Study site	Tree numbers	Circumstance (cm)	DBH (cm)	DBH^2	Basal area (m^2)	Total basal area (m^2)	Basal area (m^2 ha^{-2})
	17	108.3	34.5	1,189.1	0.1		
	18	98.8	31.4	988.0	0.1		
	19	159.5	50.8	2,577.6	0.2		
	20	105.0	33.4	1,117.1	0.1		
	21	115.3	36.7	1,347.7	0.1		
	22	162.0	51.6	2,659.1	0.2		

Study site	Tree numbers	Circumstance (cm)	DBH (cm)	DBH^2	Basal area (m^2)	Total basal area (m^2)	Basal area (m^2 ha^{-2})
	23	189.0	60.2	3,619.3	0.3		
	24	176.0	56.0	3,138.5	0.2		
	25	159.0	50.6	2,561.5	0.2		
	26	152.0	48.4	2,340.9	0.2		
	27	100.5	32.0	1,023.4	0.1		
	28	166.0	52.8	2,792.0	0.2		
	29	165.0	52.5	2,758.5	0.2		
	30	139.0	44.2	1,957.6	0.2		
	31	116.0	36.9	1,363.4	0.1		
	32	143.3	45.6	2,081.6	0.2		
	33	142.0	45.2	2,043.0	0.2		
Mixed land use (Sampling area is 0.3 ha)	1	75.5	24.0	577.6	0.0	2.5	10.2
	2	109.7	34.9	1,218.6	0.1		
	3	117.0	37.2	1,387.0	0.1		
	4	74.0	23.6	554.8	0.0		
	5	97.5	31.0	963.2	0.1		
	6	174.0	55.4	3,067.6	0.2		
	7	147.5	47.0	2,204.4	0.2		
	8	152.5	48.5	2,356.3	0.2		
	9	109.0	34.7	1,203.8	0.1		
	10	176.0	56.0	3,138.5	0.2		
	11	160.0	50.9	2,593.8	0.2		
	12	112.5	35.8	1,282.3	0.1		
	13	116.5	37.1	1,375.2	0.1		
	14	170.0	54.1	2,928.2	0.2		
	15	190.0	60.5	3,657.7	0.3		
	16	92.5	29.4	866.9	0.1		
	17	74.8	23.8	566.1	0.0		

Appendix 2 Litter fall, maize production and residual biomass

Litter fall of reforestation

Month	dry mass kg ha^{-1}
Nov-09	850.54
Dec-09	687.84
Jan-10	497.20
Feb-10	529.35
Mar-10	737.74
Apr-10	422.94

n=3

Maize production

Study site	dry mass kg ha^{-1}
Site1	2,124.86
Site2	7,798.64
Site3	8,246.78

n=3

Maize residual

Study site	kg ha^{-1}
Site1	2124.863
Site2	7798.643
Site3	8246.776

n=3

Appendix 3 Tree biomass, C and N content, and N fixation

Study	Tree	DBH	Biomass (kg)						Carbon (kg C)						Nitrogen (kg N)				Nfix
site 1	number		AGB	Root	Stem	Branch	Leaf	Total	AGB	Root	Stem	Branch	Leaf	Total	Leaf	Wood	Root	Total	(kg N)
Reforest	1	32.8	436.2	31.5	699.3	86.0	14.6	463.4	218.1	15.7	349.6	43.0	7.3	231.7	0.2	11.8	0.5	231.7	0.4
	2	35.7	514.8	37.1	864.6	112.7	17.5	565.4	257.4	18.5	432.3	56.3	8.8	282.7	0.3	14.7	0.6	282.7	0.5
	3	35.7	514.8	37.1	864.6	112.7	17.5	565.4	257.4	18.5	432.3	56.3	8.8	282.7	0.3	14.7	0.6	282.7	0.5
	4	27.4	305.3	22.1	442.7	48.1	9.8	301.9	152.7	11.1	221.4	24.0	4.9	150.9	0.1	7.4	0.3	150.9	0.3
	5	30.6	379.5	27.4	585.0	68.6	12.5	392.0	189.8	13.7	292.5	34.3	6.2	196.0	0.2	9.8	0.4	196.0	0.4
	6	21.6	191.5	13.9	243.6	22.5	5.8	172.4	95.7	7.0	121.8	11.2	2.9	86.2	0.1	4.0	0.2	86.2	0.2
	7	10.5	45.9	3.4	39.1	2.2	1.2	31.0	23.0	1.7	19.5	1.1	0.6	15.5	0.0	0.6	0.1	15.5	0.0
	8	49.0	966.5	69.0	1937.7	314.6	35.3	1205.0	483.3	34.5	968.9	157.3	17.6	602.5	0.5	33.8	1.0	602.5	1.0
	9	52.5	1107.9	79.0	2307.9	393.0	41.0	1419.7	553.9	39.5	1153.9	196.5	20.5	709.8	0.6	40.5	1.2	709.8	1.2
	10	32.4	425.7	30.7	677.7	82.7	14.2	450.0	212.8	15.4	338.8	41.3	7.1	225.0	0.2	11.4	0.5	225.0	0.4
	11	39.1	616.7	44.3	1089.5	151.2	21.4	702.3	308.3	22.1	544.8	75.6	10.7	351.2	0.3	18.6	0.7	351.2	0.6
	12	49.0	966.5	69.0	1937.7	314.6	35.3	1205.0	483.3	34.5	968.9	157.3	17.6	602.5	0.5	33.8	1.0	602.5	1.0
	13	34.1	472.5	34.0	774.7	98.0	15.9	510.1	236.3	17.0	387.4	49.0	8.0	255.1	0.2	13.1	0.5	255.1	0.5
	14	36.9	551.8	39.7	945.0	126.2	18.9	614.6	275.9	19.8	472.5	63.1	9.5	307.3	0.3	16.1	0.6	307.3	0.6
	15	32.5	427.9	30.9	682.2	83.4	14.3	452.8	213.9	15.4	341.1	41.7	7.1	226.4	0.2	11.5	0.5	226.4	0.4
	16	47.0	887.5	63.5	1737.1	273.8	32.1	1087.7	443.8	31.7	868.6	136.9	16.0	543.8	0.5	30.2	1.0	543.8	0.9
	17	43.3	755.9	54.1	1414.2	210.8	26.8	896.9	377.9	27.1	707.1	105.4	13.4	448.4	0.4	24.4	0.8	448.4	0.8
	18	14.5	86.7	6.4	88.2	6.2	2.4	66.5	43.3	3.2	44.1	3.1	1.2	33.3	0.0	1.4	0.1	33.3	0.1
	19	21.2	183.6	13.4	230.7	21.0	5.6	163.9	91.8	6.7	115.4	10.5	2.8	81.9	0.1	3.8	0.2	81.9	0.2
	20	50.6	1029.6	73.5	2101.1	348.8	37.8	1300.1	514.8	36.7	1050.6	174.4	18.9	650.0	0.6	36.7	1.1	650.0	1.1
	21	42.3	723.2	51.8	1336.4	196.1	25.6	850.6	361.6	25.9	668.2	98.1	12.8	425.3	0.4	23.0	0.8	425.3	0.8
	22	22.4	206.1	15.0	267.6	25.3	6.3	188.3	103.0	7.5	133.8	12.7	3.2	94.1	0.1	4.4	0.2	94.1	0.2
	23	32.6	432.0	31.2	690.7	84.7	14.4	458.1	216.0	15.6	345.3	42.3	7.2	229.0	0.2	11.6	0.5	229.0	0.4
	24	26.3	281.2	20.4	398.5	42.1	9.0	273.5	140.6	10.2	199.2	21.0	4.5	136.7	0.1	6.6	0.3	136.7	0.3
	25	29.5	354.5	25.6	536.1	61.4	11.6	361.2	177.3	12.8	268.1	30.7	5.8	180.6	0.2	9.0	0.4	180.6	0.4
	26	36.2	531.3	38.2	900.3	118.6	18.2	587.3	265.7	19.1	450.1	59.3	9.1	293.6	0.3	15.3	0.6	293.6	0.5
	27	19.1	149.8	10.9	177.8	15.1	4.5	128.3	74.9	5.5	88.9	7.5	2.2	64.2	0.1	2.9	0.2	64.2	0.2
Mixed landuse	1	56.0	1258.7	89.6	2717.9	483.9	47.3	1655.0	629.4	44.8	1359.0	242.0	23.6	827.5	0.7	48.0	1.3	827.5	1.3
	2	39.6	633.7	45.5	1128.2	158.1	22.1	725.7	316.8	22.7	564.1	79.1	11.0	362.8	0.3	19.3	0.7	362.8	0.7
	3	39.2	619.6	44.5	1096.3	152.4	21.5	706.4	309.8	22.2	548.2	76.2	10.8	353.2	0.3	18.7	0.7	353.2	0.6
	4	49.0	966.5	69.0	1937.7	314.6	35.3	1205.0	483.3	34.5	968.9	157.3	17.6	602.5	0.5	33.8	1.0	602.5	1.0
	5	44.6	800.5	57.3	1521.9	231.4	28.6	960.8	400.2	28.6	761.0	115.7	14.3	480.4	0.4	26.3	0.9	480.4	0.8
	6	10.2	43.2	3.2	36.2	2.0	1.1	28.8	21.6	1.6	18.1	1.0	0.6	14.4	0.0	0.6	0.0	14.4	0.0
	7	79.6	2520.2	177.9	6614.4	1500.4	102.2	3810.3	1260.1	89.0	3307.2	750.2	51.1	1905.1	1.5	121.7	2.7	1905.1	2.7
	8	49.8	996.6	71.1	2015.1	330.7	36.5	1250.1	498.3	35.6	1007.6	165.4	18.2	625.1	0.5	35.2	1.1	625.1	1.0
	9	57.6	1330.4	94.7	2917.9	529.7	50.3	1768.9	665.2	47.3	1458.9	264.8	25.1	884.4	0.8	51.7	1.4	884.4	1.4
	10	68.8	1887.4	133.7	4566.8	936.5	74.1	2692.2	943.7	66.9	2283.4	468.3	37.1	1346.1	1.1	82.6	2.0	1346.1	2.0
	11	49.0	966.5	69.0	1937.7	314.6	35.3	1205.0	483.3	34.5	968.9	157.3	17.6	602.5	0.5	33.8	1.0	602.5	1.0
	12	49.3	979.0	69.9	1969.8	321.3	35.8	1223.7	489.5	35.0	984.9	160.6	17.9	611.9	0.5	34.4	1.0	611.9	1.0
	13	61.8	1526.1	108.4	3478.6	662.4	58.6	2085.8	763.0	54.2	1739.3	331.2	29.3	1042.9	0.9	62.1	1.6	1042.9	1.6
	14	51.3	1058.0	75.5	2175.6	364.6	39.0	1343.2	529.0	37.7	1087.8	182.3	19.5	671.6	0.6	38.1	1.1	671.6	1.1
	15	51.2	1055.4	75.3	2168.7	363.1	38.9	1339.3	527.7	37.6	1084.4	181.6	19.4	669.6	0.6	38.0	1.1	669.6	1.1
Total	42		30187.0	2157.7	60253.0	10086.0	1096.1	37413.8	15093.5	1078.8	30126.5	5043.0	548.0	18706.9	16.4	1055.1	32.4	18706.9	31.7

Study	Tree	DBH	Biomass (kg)						Carbon (kg C)						Nitrogen (kg N)				Nfix
site 2	number		AGB	Root	Stem	Branch	Leaf	Total	AGB	Root	Stem	Branch	Leaf	Total	Leaf	Wood	Root	Total	(kg N)
Reforestation	1	50.1	1010.5	72.1	2051.3	338.3	37.1	1271.1	505.2	36.1	1025.6	169.1	18.5	635.6	0.6	35.8	1.1	635.6	1.1
	2	49.2	974.8	69.6	1959.0	319.0	35.6	1217.5	487.4	34.8	979.5	159.5	17.8	608.7	0.5	34.2	1.0	608.7	1.0
	3	46.5	869.8	62.2	1692.7	264.9	31.4	1061.6	434.9	31.1	846.4	132.5	15.7	530.8	0.5	29.4	0.9	530.8	0.9
	4	40.7	670.5	48.1	1212.8	173.3	23.5	776.6	335.2	24.0	606.4	86.7	11.7	388.3	0.4	20.8	0.7	388.3	0.7
	5	92.6	3403.2	239.4	9718.9	2448.1	142.7	5465.9	1701.6	119.7	4859.4	1224.1	71.3	2733.0	2.1	182.5	3.6	2733.0	3.7
	6	56.3	1272.9	90.6	2757.2	492.8	47.9	1677.4	636.5	45.3	1378.6	246.4	23.9	838.7	0.7	48.8	1.4	838.7	1.4
	7	41.0	678.2	48.6	1230.9	176.6	23.8	787.4	339.1	24.3	615.4	88.3	11.9	393.7	0.4	21.1	0.7	393.7	0.7
	8	54.1	1175.3	83.7	2489.2	432.7	43.8	1524.0	587.6	41.9	1244.6	216.4	21.9	762.0	0.7	43.8	1.3	762.0	1.2
	9	63.6	1615.5	114.7	3741.8	726.8	62.4	2233.5	807.8	57.3	1870.9	363.4	31.2	1116.7	0.9	67.0	1.7	1116.7	1.7
	10	43.4	758.6	54.3	1420.8	212.0	27.0	900.8	379.3	27.2	710.4	106.0	13.5	450.4	0.4	24.5	0.8	450.4	0.8
	11	25.8	271.2	19.7	380.4	39.6	8.6	261.8	135.6	9.8	190.2	19.8	4.3	130.9	0.1	6.3	0.3	130.9	0.3
	12	62.4	1557.4	110.6	3570.2	684.7	59.9	2137.2	778.7	55.3	1785.1	342.3	29.9	1068.6	0.9	63.8	1.7	1068.6	1.7
	13	49.7	991.5	70.8	2002.1	328.0	36.3	1242.6	495.8	35.4	1001.1	164.0	18.1	621.3	0.5	35.0	1.1	621.3	1.0
	14	52.8	1121.2	79.9	2343.5	400.7	41.6	1440.2	560.6	40.0	1171.7	200.4	20.8	720.1	0.6	41.2	1.2	720.1	1.2
	15	60.8	1479.8	105.1	3343.9	629.9	56.6	2010.0	739.9	52.6	1671.9	315.0	28.3	1005.0	0.8	59.6	1.6	1005.0	1.6
	16	42.3	723.2	51.8	1336.4	196.1	25.6	850.6	361.6	25.9	668.2	98.1	12.8	425.3	0.4	23.0	0.8	425.3	0.8
	17	34.5	482.0	34.7	794.7	101.2	16.3	522.5	241.0	17.4	397.3	50.6	8.1	261.2	0.2	13.4	0.5	261.2	0.5
	18	31.4	401.3	29.0	628.4	75.1	13.3	419.2	200.7	14.5	314.2	37.5	6.6	209.6	0.2	10.6	0.4	209.6	0.4
	19	50.8	1036.0	73.9	2117.9	352.3	38.1	1309.8	518.0	37.0	1059.0	176.2	19.0	654.9	0.6	37.1	1.1	654.9	1.1
	20	33.4	453.1	32.7	734.2	91.5	15.2	485.1	226.6	16.3	367.1	45.8	7.6	242.5	0.2	12.4	0.5	242.5	0.5
	21	36.7	545.6	39.2	931.3	123.9	18.7	606.3	272.8	19.6	465.7	61.9	9.3	303.1	0.3	15.8	0.6	303.1	0.6
	22	51.6	1068.4	76.2	2203.0	370.4	39.4	1359.1	534.2	38.1	1101.5	185.2	19.7	679.6	0.6	38.6	1.1	679.6	1.1
	23	60.2	1449.3	103.0	3255.9	608.9	55.3	1960.3	724.6	51.5	1627.9	304.5	27.7	980.2	0.8	58.0	1.5	980.2	1.5
	24	56.0	1258.7	89.6	2717.9	483.9	47.3	1655.0	629.4	44.8	1359.0	242.0	23.6	827.5	0.7	48.0	1.3	827.5	1.3
	25	50.6	1029.6	73.5	2101.1	348.8	37.8	1300.1	514.8	36.7	1050.6	174.4	18.9	650.0	0.6	36.7	1.1	650.0	1.1
	26	48.4	941.9	67.3	1874.6	301.6	34.3	1168.2	470.9	33.6	937.3	150.8	17.1	584.1	0.5	32.6	1.0	584.1	1.0
	27	32.0	415.5	30.0	657.1	79.5	13.8	437.1	207.8	15.0	328.5	39.7	6.9	218.6	0.2	11.0	0.4	218.6	0.4
	28	52.8	1121.2	79.9	2343.5	400.7	41.6	1440.2	560.6	40.0	1171.7	200.4	20.8	720.1	0.6	41.2	1.2	720.1	1.2
	29	52.5	1107.9	79.0	2307.9	393.0	41.0	1419.7	553.9	39.5	1153.9	196.5	20.5	709.8	0.6	40.5	1.2	709.8	1.2
	30	44.2	789.2	56.5	1494.5	226.1	28.2	944.6	394.6	28.3	747.3	113.1	14.1	472.3	0.4	25.8	0.8	472.3	0.8
	31	36.9	551.8	39.7	945.0	126.2	18.9	614.6	275.9	19.8	472.5	63.1	9.5	307.3	0.3	16.1	0.6	307.3	0.6
	32	45.6	838.6	60.0	1615.5	249.6	30.1	1016.1	419.3	30.0	807.7	124.8	15.1	508.0	0.5	28.0	0.9	508.0	0.9
	33	45.2	823.3	58.9	1577.6	242.2	29.5	993.8	411.6	29.5	788.8	121.1	14.8	496.9	0.4	27.3	0.9	496.9	0.9
Mixed	1	24.0	236.0	17.1	318.3	31.6	7.4	221.5	118.0	8.6	159.1	15.8	3.7	110.8	0.1	5.2	0.3	110.8	0.2
landuse	2	34.9	493.8	35.6	819.7	105.3	16.7	537.9	246.9	17.8	409.9	52.7	8.4	268.9	0.3	13.9	0.5	268.9	0.5
	3	37.2	561.3	40.4	965.8	129.7	19.3	627.3	280.6	20.2	482.9	64.9	9.6	313.6	0.3	16.4	0.6	313.6	0.6
	4	23.6	226.8	16.5	302.5	29.6	7.1	211.2	113.4	8.2	151.3	14.8	3.5	105.6	0.1	5.0	0.2	105.6	0.2
	5	31.0	391.3	28.3	608.5	72.1	12.9	406.7	195.7	14.1	304.2	36.0	6.5	203.4	0.2	10.2	0.4	203.4	0.4
	6	55.4	1230.6	87.6	2640.4	466.4	46.1	1610.6	615.3	43.8	1320.2	233.2	23.1	805.3	0.7	46.6	1.3	805.3	1.3
	7	47.0	887.5	63.5	1737.1	273.8	32.1	1087.7	443.8	31.7	868.6	136.9	16.0	543.8	0.5	30.2	1.0	543.8	0.9
	8	48.5	948.0	67.7	1890.2	304.9	34.5	1177.3	474.0	33.9	945.1	152.4	17.3	588.7	0.5	32.9	1.0	588.7	1.0
	9	34.7	487.9	35.1	807.1	103.3	16.5	530.1	244.0	17.6	403.6	51.6	8.3	265.1	0.2	13.7	0.5	265.1	0.5
	10	56.0	1258.7	89.6	2717.9	483.9	47.3	1655.0	629.4	44.8	1359.0	242.0	23.6	827.5	0.7	48.0	1.3	827.5	1.3
	11	50.9	1042.5	74.4	2134.8	355.9	38.4	1319.6	521.2	37.2	1067.4	177.9	19.2	659.8	0.6	37.4	1.1	659.8	1.1
	12	35.8	519.4	37.4	874.4	114.3	17.7	571.5	259.7	18.7	437.2	57.2	8.8	285.7	0.3	14.8	0.6	285.7	0.5
	13	37.1	556.5	40.0	955.4	128.0	19.1	620.9	278.3	20.0	477.7	64.0	9.6	310.5	0.3	16.3	0.6	310.5	0.6
	14	54.1	1175.3	83.7	2489.2	432.7	43.8	1524.0	587.6	41.9	1244.6	216.4	21.9	762.0	0.7	43.8	1.3	762.0	1.2
	15	60.5	1464.5	104.1	3299.7	619.4	55.9	1985.0	732.2	52.0	1649.8	309.7	28.0	992.5	0.8	58.8	1.6	992.5	1.6
	16	29.4	352.6	25.5	532.5	60.8	11.5	358.9	176.3	12.7	266.2	30.4	5.8	179.5	0.2	8.9	0.4	179.5	0.4
	17	23.8	231.4	16.8	310.3	30.6	7.2	216.3	115.7	8.4	155.2	15.3	3.6	108.2	0.1	5.1	0.3	108.2	0.2
	18	36.2	530.1	38.1	897.6	118.2	18.1	585.6	265.0	19.1	448.8	59.1	9.1	292.8	0.3	15.2	0.6	292.8	0.5
Total	51	2314.5	45481.3	3245.8	93852.8	16299.4	1674.2	57757.3 #	22740.7	1622.9	46926.4	8149.7	837.1	28878.6 #	25.1	1652.3	48.7	28878.6 #	48.0

Study	Tree	DBH	Biomass (kg)						Carbon (kg C)						Nitrogen (kg N)				Nfix
site 3	number		AGB	Root	Stem	Branch	Leaf	Total	AGB	Root	Stem	Branch	Leaf	Total	Leaf	Wood	Root	Total	(kg N)
Reforestation	1	94.0	3505.7	246.5	10095.6	2569.5	147.5	5664.3	1752.9	123.2	5047.8	1284.7	73.7	2832.2	2.2	190.0	3.7	2832.2	3.8
	2	47.7	917.5	65.6	1812.7	289.0	33.3	1132.0	458.8	32.8	906.4	144.5	16.6	566.0	0.5	31.5	1.0	566.0	1.0
	3	43.6	766.9	54.9	1440.7	215.8	27.3	912.6	383.5	27.5	720.3	107.9	13.6	456.3	0.4	24.8	0.8	456.3	0.8
	4	53.5	1148.1	81.8	2415.7	416.5	42.7	1481.8	574.0	40.9	1207.9	208.3	21.3	740.9	0.6	42.5	1.2	740.9	1.2
	5	97.1	3734.7	262.4	10947.8	2848.5	158.2	6111.5	1867.3	131.2	5473.9	1424.3	79.1	3055.8	2.4	206.9	3.9	3055.8	4.1
	6	62.7	1573.1	111.7	3616.5	696.0	60.6	2163.2	786.6	55.8	1808.2	348.0	30.3	1081.6	0.9	64.7	1.7	1081.6	1.7
	7	89.1	3153.5	222.0	8814.7	2162.1	131.1	4987.7	1576.7	111.0	4407.4	1081.1	65.5	2493.8	2.0	164.7	3.3	2493.8	3.4
	8	62.8	1577.9	112.0	3630.5	699.4	60.8	2171.1	788.9	56.0	1815.2	349.7	30.4	1085.5	0.9	64.9	1.7	1085.5	1.7
	9	44.6	800.5	57.3	1521.9	231.4	28.6	960.8	400.2	28.6	761.0	115.7	14.3	480.4	0.4	26.3	0.9	480.4	0.8
	10	53.5	1148.1	81.8	2415.7	416.5	42.7	1481.8	574.0	40.9	1207.9	208.3	21.3	740.9	0.6	42.5	1.2	740.9	1.2
	11	73.5	2155.4	152.4	5413.8	1162.9	85.9	3157.9	1077.7	76.2	2706.9	581.4	43.0	1578.9	1.3	98.7	2.3	1578.9	2.3
	12	23.7	229.2	16.7	306.7	30.1	7.1	213.9	114.6	8.3	153.3	15.1	3.6	107.0	0.1	5.1	0.2	107.0	0.2
	13	25.5	264.6	19.2	368.6	38.1	8.4	254.2	132.3	9.6	184.3	19.0	4.2	127.1	0.1	6.1	0.3	127.1	0.3
	14	24.0	236.0	17.1	318.3	31.6	7.4	221.5	118.0	8.6	159.1	15.8	3.7	110.8	0.1	5.2	0.3	110.8	0.2
	15	59.8	1434.1	101.9	3212.4	598.6	54.7	1935.8	717.1	51.0	1606.2	299.3	27.3	967.9	0.8	57.2	1.5	967.9	1.5
	16	43.0	744.9	53.4	1388.0	205.8	26.4	881.3	372.5	26.7	694.0	102.9	13.2	440.7	0.4	23.9	0.8	440.7	0.8
	17	47.4	905.5	64.7	1782.2	282.9	32.8	1114.1	452.7	32.4	891.1	141.4	16.4	557.1	0.5	31.0	1.0	557.1	1.0
	18	36.6	542.5	39.0	924.5	122.7	18.6	602.1	271.2	19.5	462.3	61.4	9.3	301.1	0.3	15.7	0.6	301.1	0.6
	19	51.9	1081.5	77.1	2237.7	377.9	40.0	1379.1	540.7	38.6	1118.8	188.9	20.0	689.6	0.6	39.2	1.2	689.6	1.1
	20	47.4	903.1	64.5	1776.2	281.7	32.7	1110.6	451.5	32.3	888.1	140.8	16.4	555.3	0.5	30.9	1.0	555.3	0.9
	21	44.2	789.2	56.5	1494.5	226.1	28.2	944.6	394.6	28.3	747.3	113.1	14.1	472.3	0.4	25.8	0.8	472.3	0.8
Mixed	1	41.1	680.9	48.8	1236.9	177.7	23.9	791.1	340.4	24.4	618.5	88.9	12.0	395.5	0.4	21.2	0.7	395.5	0.7
landuse	2	33.4	451.4	32.5	730.6	91.0	15.1	482.9	225.7	16.3	365.3	45.5	7.6	241.4	0.2	12.3	0.5	241.4	0.5
	3	59.7	1429.6	101.6	3199.4	595.5	54.5	1928.4	714.8	50.8	1599.7	297.8	27.2	964.2	0.8	56.9	1.5	964.2	1.5
	4	76.1	2305.6	162.9	5901.6	1297.8	92.6	3423.9	1152.8	81.5	2950.8	648.9	46.3	1712.0	1.4	108.0	2.4	1712.0	2.5
	5	57.4	1321.7	94.0	2893.4	524.0	49.9	1755.0	660.9	47.0	1446.7	262.0	25.0	877.5	0.7	51.3	1.4	877.5	1.4
	6	38.5	599.2	43.0	1050.2	144.3	20.7	678.5	299.6	21.5	525.1	72.2	10.4	339.3	0.3	17.9	0.6	339.3	0.6
	7	57.6	1327.5	94.4	2909.7	527.8	50.2	1764.2	663.8	47.2	1454.9	263.9	25.1	882.1	0.8	51.6	1.4	882.1	1.4
	8	38.8	609.7	43.8	1073.9	148.5	21.1	692.9	304.9	21.9	536.9	74.2	10.6	346.4	0.3	18.3	0.7	346.4	0.6
	9	75.9	2294.1	162.1	5864.1	1287.3	92.1	3403.5	1147.1	81.1	2932.1	643.6	46.0	1701.8	1.4	107.3	2.4	1701.8	2.5
	10	63.3	1604.9	113.9	3710.3	719.0	61.9	2215.8	802.4	57.0	1855.1	359.5	31.0	1107.9	0.9	66.4	1.7	1107.9	1.7
	11	71.9	2064.1	146.1	5121.8	1083.6	81.9	2997.9	1032.1	73.0	2560.9	541.8	40.9	1498.9	1.2	93.1	2.2	1498.9	2.2
	12	69.1	1904.7	134.9	4620.6	950.6	74.9	2722.0	952.3	67.5	2310.3	475.3	37.5	1361.0	1.1	83.6	2.0	1361.0	2.0
	13	49.5	985.3	70.3	1985.9	324.6	36.0	1233.1	492.6	35.2	992.9	162.3	18.0	616.6	0.5	34.7	1.1	616.6	1.0
	14	64.6	1669.3	118.4	3902.2	766.7	64.7	2323.1	834.7	59.2	1951.1	383.3	32.3	1161.5	1.0	70.0	1.8	1161.5	1.8
	15	51.2	1051.5	75.0	2158.5	360.9	38.7	1333.4	525.7	37.5	1079.3	180.5	19.4	666.7	0.6	37.8	1.1	666.7	1.1
Total	36	1973.7	47911.4	3400.8	112293.9	22902.3	1853.1	66627.7 #	23955.7	1700.4	56146.9	11451.2	926.6	33313.9 #	27.8	2027.9	51.0	33313.9 #	51.2

Appendix 4 Data observation at study sites

Nitrous oxide flux (µg N_2O N m^{-2} h^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	2.31	35.14	29.41	22.57	23.62	6.33	10.38	27.64	29.09	17.31	38.07	20.49
2	Reforestation	24.73	NA	29.81	10.18	17.44	28.99	15.45	28.03	38.80	23.10	18.39	37.06
3	Reforestation	37.55	18.28	57.58	54.81	37.13	20.36	10.71	12.04	13.61	24.04	35.68	16.78
4	Reforestation	21.55	NA	74.88	20.33	85.16	14.62	13.74	33.84	15.65	37.34	20.46	NA
5	Reforestation	6.57	34.58	45.54	27.91	46.68	40.84	16.63	22.42	43.24	38.76	13.50	13.52
6	Maize	25.11	31.43	14.95	10.14	23.73	13.63	9.62	19.31	43.19	22.67	14.01	NA
7	Maize	47.85	42.75	21.78	21.14	30.07	32.55	6.63	25.66	26.77	12.91	10.79	21.88
8	Maize	15.37	15.03	18.50	42.58	31.94	24.80	17.50	58.70	22.19	26.16	3.62	18.38
9	Maize	9.41	11.39	28.44	23.66	64.49	7.74	9.73	48.53	49.69	47.62	NA	39.24
10	Maize	24.74	1.28	24.56	67.82	62.33	17.88	10.63	20.54	12.13	NA	19.85	46.93
11	Reforestation	34.23	35.44	22.24	16.84	22.26	21.76	9.73	20.85	13.81	NA	9.03	38.96
12	Reforestation	14.63	NA	28.00	17.52	30.14	5.04	16.10	20.54	NA	10.07	14.63	45.41
13	Maize	18.44	25.38	14.07	22.28	21.60	31.98	21.35	66.68	15.96	56.19	17.47	45.30
14	Maize	1.87	27.50	45.26	29.57	47.16	15.46	11.40	52.28	32.11	22.30	9.81	28.39
15	Maize	17.54	26.37	43.83	20.35	26.38	41.27	24.66	14.31	38.14	13.44	40.44	25.97
16	Reforestation	20.11	59.72	54.31	NA	82.67	114.87	60.11	20.36	NA	35.74	39.40	21.85
17	Reforestation	77.82	67.95	50.60	94.18	67.12	36.27	27.57	15.23	33.84	36.06	11.70	23.36
18	Reforestation	56.92	24.01	49.99	64.30	40.98	46.32	36.26	27.76	24.25	39.57	20.05	14.12
19	Reforestation	23.41	61.64	NA	NA	126.61	58.25	20.08	10.42	36.35	13.68	38.80	9.25
20	Reforestation	13.29	31.60	NA	143.23	92.29	41.34	18.11	6.91	46.13	NA	15.95	15.98
21	Maize	25.69	25.24	27.59	20.64	25.47	10.59	9.70	15.08	NA	26.89	13.46	5.78
22	Maize	50.06	19.70	30.47	17.65	25.58	12.08	13.32	14.65	29.89	19.59	27.55	7.02
23	Maize	20.40	16.13	19.50	21.16	27.10	46.20	8.89	13.85	21.20	13.75	17.76	NA
24	Maize	23.81	19.28	15.92	50.16	20.32	20.70	13.14	21.50	17.95	10.13	13.56	17.29
25	Maize	12.39	21.64	40.40	NA	41.80	21.51	19.36	8.97	24.71	16.48	5.26	15.03
26	Reforestation	77.78	49.98	NA	NA	111.32	93.03	50.09	50.99	49.55	NA	44.15	56.26
27	Reforestation	32.21	31.37	NA	NA	65.78	112.90	29.90	23.96	47.11	27.70	26.34	38.86
28	Reforestation	68.75	79.71	NA	NA	91.32	NA	44.35	32.80	58.12	37.11	18.86	35.75
29	Maize	45.78	24.79	NA	25.21	53.11	40.51	24.22	8.92	16.50	NA	23.96	22.84
30	Maize	11.21	23.34	23.42	40.08	58.20	28.31	10.15	26.72	18.72	15.21	10.43	6.25
31	Reforest	31.27	54.47	49.70	31.37	20.01	33.78	25.61	29.45	59.14	52.84	25.89	24.03
32	Reforest	103.14	28.76	NA	56.04	42.96	53.80	24.24	40.79	NA	14.73	21.89	9.28
33	Reforest	76.11	53.49	62.22	52.78	40.84	76.00	22.42	35.93	46.22	25.23	41.74	15.82
34	Reforest	31.78	NA	49.27	30.28	NA	60.80	34.05	48.07	35.52	NA	22.99	19.79
35	Reforest	52.63	33.20	NA	40.37	36.80	72.37	28.19	20.46	NA	77.75	39.92	16.98
36	Maize	52.15	38.85	40.29	21.45	NA	31.29	10.88	14.74	60.69	12.06	NA	9.62
37	Maize	42.43	42.71	65.36	40.83	NA	37.40	2.62	24.39	37.95	40.41	11.77	14.24
38	Maize	46.08	58.19	16.11	56.25	NA	45.49	16.33	13.10	23.35	16.84	18.68	11.23
39	Maize	13.43	23.96	29.28	45.23	38.44	63.18	19.51	21.16	63.95	48.78	14.41	11.07
40	Maize	29.15	30.96	25.09	22.79	42.73	32.33	11.11	4.80	42.38	15.76	11.31	2.42
41	Reforestation	40.91	21.53	67.08	67.19	58.71	NA	38.97	42.22	NA	50.41	42.74	26.33
42	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	32.05	15.00
43	Reforestation	20.82	33.91	29.93	25.89	66.17	29.55	23.22	34.19	57.16	22.34	18.88	5.28
44	Maize	23.90	28.87	26.60	27.14	3.49	25.91	19.59	13.56	NA	12.48	24.65	4.63
45	Maize	20.33	25.15	19.31	56.08	NA	52.56	14.30	19.90	13.20	24.09	27.27	33.33

Reforest	Mean	39.48	41.93	46.70	45.63	57.43	48.36	26.18	27.49	38.09	32.43	26.57	23.64
	SD	26.87	17.38	15.77	33.69	31.25	32.18	13.37	11.74	14.94	16.59	11.27	13.08
	STD error	5.73	4.10	4.07	8.17	6.82	7.20	2.85	2.50	3.62	3.91	2.35	2.79
Maize	Mean	26.23	26.36	28.13	32.49	35.77	29.70	13.85	23.97	30.53	23.69	16.80	19.34
	SD	14.72	11.92	12.71	15.53	16.46	14.55	5.77	16.91	15.24	13.71	8.69	13.49
	STD error	3.14	2.54	2.77	3.39	3.88	3.10	1.23	3.60	3.41	3.07	1.94	3.02

Denitrification (mg N_2O N kg^{-1} h^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	NA	0.00724	0.00828	0.00040	0.00060	0.00010	0.00012	0.00009	NA	0.00061	NA	0.00021
2	Reforestation	0.00115	0.00862	0.00460	0.00286	NA	0.00083	0.00571	0.00107	NA	NA	NA	NA
3	Reforestation	0.00072	0.00606	0.00845	NA	0.00771	0.00006	0.00338	0.00018	NA	NA	0.00048	NA
4	Reforestation	0.00139	0.00626	0.00165	0.00029	NA	0.00072	0.00004	0.00013	NA	NA	NA	NA
5	Reforestation	0.00104	0.00632	0.00702	0.00056	0.00219	0.00007	0.00017	0.00019	0.00095	0.00072	0.00027	NA
6	Maize	0.00093	0.00513	0.00556	0.00064	0.00081	0.00026	0.00011	0.00027	NA	NA	NA	0.00040
7	Maize	0.00069	0.00450	0.00343	0.00015	0.00038	0.00008	0.00006	0.00006	NA	NA	NA	NA
8	Maize	0.00049	0.00552	0.00676	0.00165	0.00118	0.00005	0.00033	0.00029	NA	NA	NA	0.00060
9	Maize	0.00127	0.00408	0.00569	0.00017	0.00549	0.00007	0.00022	0.00020	NA	NA	NA	NA
10	Maize	0.00090	0.00376	0.00638	0.00617	0.00852	0.00011	0.00021	0.00018	0.00003	NA	0.00039	0.00051
11	Reforestation	0.00464	0.00886	0.00381	0.00024	0.00016	0.00001	0.00004	0.00007	NA	NA	0.00015	0.00029
12	Reforestation	0.00066	0.00515	0.00424	NA	0.00046	0.00039	0.00037	0.00020	NA	NA	NA	NA
13	Maize	0.00363	0.00463	0.00520	0.00133	0.00386	0.00014	0.00019	0.00017	0.00008	NA	NA	0.00056
14	Maize	0.00793	0.00497	0.00629	0.00776	0.00433	0.00008	0.00035	0.00013	NA	NA	NA	NA
15	Maize	0.00235	0.00350	0.00647	0.00182	0.00093	0.00002	0.00026	0.00010	0.00033	NA	NA	0.00029
16	Reforestation	0.00581	0.00504	0.00577	0.00678	0.01721	0.00050	0.00008	0.00023	NA	0.00116	0.00030	0.00055
17	Reforestation	0.00133	0.00577	0.00321	0.00647	0.00344	0.00024	0.00022	0.00041	NA	NA	NA	NA
18	Reforestation	0.00046	0.00413	0.00563	0.00474	0.00106	0.00021	0.00039	0.00061	NA	0.00062	NA	0.00028
19	Reforestation	0.00672	0.00514	0.00457	0.00643	0.00098	0.00073	0.00088	0.00080	NA	NA	NA	NA
20	Reforestation	0.00333	0.00567	0.00417	NA	0.00634	0.00051	0.00102	0.00037	NA	0.00067	0.00052	0.00048
21	Maize	0.00109	0.00444	0.00419	0.00010	0.01617	0.00028	0.00001	0.00055	0.00090	0.00009	NA	NA
22	Maize	0.00094	0.00434	0.00280	0.00011	0.00126	0.00029	0.00020	0.00034	NA	NA	NA	NA
23	Maize	0.00075	0.00377	0.00331	0.00749	0.00027	0.00192	0.00153	0.00049	NA	NA	NA	NA
24	Maize	0.00177	0.00297	0.00493	0.01201	0.00057	0.00020	0.00080	0.00054	NA	NA	NA	NA
25	Maize	0.00873	0.00361	0.00459	0.00547	0.00556	0.00035	0.00033	0.00025	NA	NA	NA	NA
26	Reforestation	0.00163	0.00348	0.00294	0.00257	0.01010	0.00229	0.00049	0.00031	NA	0.00097	0.00104	0.00067
27	Reforestation	0.00079	0.00199	0.01154	NA	0.00366	0.00383	0.00138	0.00021	NA	NA	NA	NA
28	Reforestation	0.00036	0.00420	0.00892	0.01558	0.01371	0.00080	0.00051	0.00031	NA	0.00152	0.00054	0.00054
29	Maize	0.00060	0.00565	0.00482	0.00016	0.00247	0.00050	0.00013	0.00105	NA	NA	NA	NA
30	Maize	0.00201	0.00392	0.00418	0.00131	0.00153	0.00011	0.00007	0.00022	0.00056	0.00023	0.00035	NA
31	Reforestation	0.00129	0.00508	0.00774	0.01558	0.00346	0.00061	0.00010	0.00331	0.00105	NA	0.00513	0.00018
32	Reforestation	0.00094	0.00734	0.00508	0.00725	NA	0.00107	0.00025	0.00028	NA	NA	NA	NA
33	Reforestation	0.00164	0.00448	0.00835	NA	NA	0.00048	0.00004	0.00012	NA	NA	0.00055	0.00023
34	Reforestation	0.00420	0.00554	0.00596	0.00068	0.01107	0.00444	0.00008	0.00008	NA	NA	NA	NA
35	Reforestation	0.00238	0.00275	0.00399	0.00177	0.01225	0.00022	0.00044	0.00023	0.00223	NA	0.00069	0.00005
36	Maize	0.00098	0.00432	0.00532	0.00037	0.00874	0.00008	0.00016	0.00019	0.00717	NA	0.00043	NA
37	Maize	0.00027	0.00623	0.00549	0.00161	0.00535	0.00134	0.00004	NA	NA	NA	NA	NA
38	Maize	0.00033	0.00290	0.00480	0.00382	0.01485	0.00001	0.00012	0.00012	0.00364	NA	NA	0.00021
39	Maize	0.00151	0.00314	0.00622	0.00122	0.00469	0.00014	0.00036	NA	NA	NA	NA	NA
40	Maize	0.00063	0.00457	0.00563	NA	0.01557	0.00010	0.00008	NA	0.00061	NA	0.00048	0.00023
41	Reforestation	NA	0.00322	0.00384	0.00142	0.00335	0.00020	0.00012	0.00027	NA	NA	0.00042	0.00125
42	Reforestation	0.00113	0.00607	0.00615	NA	0.01283	NA	0.00603	0.00031	NA	NA	NA	NA
43	Reforestation	0.00051	0.00597	0.00611	0.00033	NA	0.00087	0.00014	0.00016	0.00574	NA	NA	0.00021
44	Maize	0.00324	0.00512	0.00748	0.00017	0.00790	0.00026	0.00008	0.00007	NA	NA	NA	NA
45	Maize	0.00410	0.00596	0.00610	0.00077	0.00852	0.00015	0.00005	0.00010	0.00073	0.00062	0.00046	0.00027

Reforestati	Mean	0.00201	0.00541	0.00574	0.00435	0.00614	0.00087	0.00096	0.00043	0.00249	0.00090	0.00092	0.00041
	SD	0.00184	0.00170	0.00233	0.00493	0.00542	0.00117	0.00171	0.00067	0.00224	0.00034	0.00142	0.00032
	STD error	0.00040	0.00036	0.00049	0.00120	0.00128	0.00025	0.00036	0.00014	0.00112	0.00013	0.00043	0.00009

Maize	Mean	0.00205	0.00441	0.00526	0.00259	0.00541	0.00030	0.00026	0.00028	0.00156	0.00031	0.00042	0.00038
	SD	0.00229	0.00094	0.00119	0.00330	0.00500	0.00046	0.00033	0.00024	0.00237	0.00027	0.00006	0.00016
	STD error	0.00049	0.00020	0.00025	0.00072	0.00106	0.00010	0.00007	0.00005	0.00079	0.00016	0.00002	0.00005

N_2O : $N_2O + N_2$ ratio

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	0.12	0.77	0.21	0.32	0.18	0.87	0.67	1.35	NA	3.62	NA	0.00
2	Reforestation	6.46	1.64	0.38	0.04	0.25	9.24	0.07	0.10	NA	NA	NA	NA
3	Reforestation	1.30	0.64	0.17	NA	0.16	3.30	0.05	0.70	NA	NA	NA	NA
4	Reforestation	0.91	1.17	0.33	9.29	0.05	0.65	2.39	0.90	NA	NA	NA	NA
5	Reforestation	0.63	0.37	0.14	0.18	0.15	1.06	0.71	NA	NA	0.68	NA	NA
6	Maize	2.27	1.47	0.21	0.37	0.29	0.60	0.47	0.02	NA	NA	NA	NA
7	Maize	0.57	1.02	0.60	1.93	0.91	1.20	1.36	2.00	NA	NA	NA	NA
8	Maize	1.78	0.84	0.18	0.12	2.31	5.09	0.94	1.26	NA	NA	NA	0.71
9	Maize	0.84	1.62	0.30	0.67	0.02	2.21	0.29	0.42	NA	NA	NA	NA
10	Maize	0.48	0.69	0.28	0.10	0.12	1.72	0.90	0.14	NA	NA	NA	NA
11	Reforestation	0.06	0.60	0.60	0.47	1.06	9.12	3.20	1.15	NA	NA	NA	NA
12	Reforestation	0.92	0.56	0.58	NA	10.68	0.73	0.65	1.79	NA	NA	NA	NA
13	Maize	0.06	0.61	0.67	0.03	0.09	NA	1.88	3.12	NA	NA	NA	NA
14	Maize	0.06	0.58	0.18	0.02	0.04	4.03	0.99	4.47	NA	NA	NA	NA
15	Maize	0.36	1.82	0.36	0.09	0.80	4.11	0.39	8.19	2.81	NA	NA	1.20
16	Reforestation	0.52	0.21	0.38	0.20	0.26	0.16	1.68	0.49	0.71	1.73	2.63	3.05
17	Reforestation	0.35	0.18	0.64	0.10	0.05	8.70	2.19	0.56	NA	NA	NA	NA
18	Reforestation	3.29	5.19	0.31	0.18	1.16	3.97	0.64	0.32	4.62	0.65	NA	NA
19	Reforestation	0.16	2.85	1.07	2.48	2.58	0.45	0.50	0.35	NA	NA	NA	NA
20	Reforestation	0.31	4.11	1.29	0.28	0.24	0.20	0.04	0.23	0.12	1.60	NA	0.66
21	Maize	0.92	2.33	0.65	0.47	0.09	0.25	11.16	0.46	1.13	NA	NA	NA
22	Maize	1.52	2.71	0.62	0.41	0.25	1.49	0.66	0.79	NA	NA	NA	NA
23	Maize	2.35	4.23	0.50	0.12	0.16	0.66	0.50	1.18	NA	NA	NA	NA
24	Maize	0.85	3.89	0.41	0.07	NA	0.88	0.58	0.38	NA	NA	NA	NA
25	Maize	0.12	5.62	0.59	0.36	0.02	0.73	0.91	0.76	NA	NA	NA	NA
26	Reforestation	0.26	2.57	0.37	3.30	0.49	0.13	0.58	1.29	NA	1.32	NA	0.94
27	Reforestation	0.81	6.13	0.15	0.02	NA	0.27	0.11	2.79	NA	NA	NA	NA
28	Reforestation	6.25	3.93	0.26	0.05	0.05	0.38	0.84	0.40	0.34	1.12	NA	0.80
29	Maize	0.87	1.96	0.41	5.05	0.05	0.12	1.41	0.07	NA	NA	NA	NA
30	Maize	0.23	5.02	0.75	0.79	0.24	0.66	1.29	0.57	1.32	NA	NA	NA
31	Reforestation	0.03	0.62	0.25	0.01	0.93	0.19	4.24	0.14	2.58	NA	7.24	3.53
32	Reforestation	0.87	0.33	0.28	0.63	0.20	0.07	0.58	2.64	NA	NA	NA	NA
33	Reforestation	0.04	0.22	0.41	0.04	0.09	0.89	2.38	2.57	11.71	NA	6.19	NA
34	Reforestation	0.01	0.18	0.53	0.40	0.77	0.01	1.07	1.30	NA	NA	NA	NA
35	Reforestation	1.72	0.63	0.88	0.21	0.59	0.09	0.45	0.95	2.72	NA	1.09	NA
36	Maize	0.48	0.33	0.46	0.67	0.87	NA	0.82	0.65	2.45	NA	NA	NA
37	Maize	1.43	0.26	0.76	0.63	NA	0.17	2.26	NA	NA	NA	NA	NA
38	Maize	3.60	0.60	0.50	NA	0.60	-14.54	0.74	0.63	8.43	NA	NA	NA
39	Maize	0.15	0.52	0.90	0.19	0.56	0.54	0.51	NA	NA	NA	NA	NA
40	Maize	0.70	0.22	0.39	NA	0.24	0.54	1.05	NA	NA	NA	NA	NA
41	Reforestation	NA	0.23	1.16	0.91	NA	1.07	3.30	0.94	1.83	NA	1.01	0.55
42	Reforestation	0.33	0.52	0.72	0.03	0.15	0.09	0.07	0.18	NA	NA	NA	NA
43	Reforestation	0.15	0.27	0.31	NA	0.15	0.20	1.94	0.80	0.13	NA	NA	3.32
44	Maize	0.23	0.84	0.42	0.77	0.50	2.73	1.29	2.13	NA	NA	NA	NA
45	Maize	NA	0.48	0.38	0.09	0.57	0.45	2.98	3.53	0.62	NA	0.77	NA

Reforest	Mean	1.16	1.47	0.50	0.96	0.96	1.82	1.23	1.00	2.75	1.53	3.63	1.61
	SD	1.84	1.77	0.33	2.14	2.30	3.02	1.20	0.82	3.68	1.01	2.91	1.44
	STD error	0.39	0.37	0.07	0.48	0.50	0.63	0.25	0.17	1.23	0.38	1.30	0.51
Maize	Mean	0.95	1.71	0.48	0.65	0.44	0.68	1.52	1.62	2.80	NA	NA	0.96
	SD	0.92	1.61	0.20	1.13	0.53	3.86	2.25	2.03	2.88	NA	NA	0.35
	STD error	0.20	0.34	0.04	0.25	0.12	0.86	0.48	0.46	1.18	NA	NA	0.25

N mineralization (mg N kg^{-1} h^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	0.31	0.20	NA	0.15	NA	0.82	NA	0.25	NA	0.44	NA	0.35
2	Reforestation	-0.01	0.41	NA	0.03	NA	NA	NA	NA	NA	NA	NA	NA
3	Reforestation	-0.24	0.83	NA	0.23	NA	0.11	NA	0.51	NA	0.11	NA	0.06
4	Reforestation	0.21	0.71	NA	-0.05	NA	NA	NA	NA	NA	NA	NA	NA
5	Reforestation	0.03	0.29	NA	0.12	NA	0.57	NA	0.22	NA	0.21	NA	0.41
6	Maize	-0.05	-0.09	NA	0.03	NA	NA	NA	NA	NA	NA	NA	NA
7	Maize	0.11	0.02	NA	0.00	NA	NA	NA	NA	NA	NA	NA	NA
8	Maize	0.11	0.25	NA	0.13	NA	0.19	NA	0.23	NA	0.06	NA	0.22
9	Maize	-0.02	0.13	NA	0.10	NA	NA	NA	NA	NA	NA	NA	NA
10	Maize	0.03	0.26	NA	0.11	NA	0.73	NA	-0.31	NA	0.47	NA	0.37
11	Reforestation	0.15	0.28	NA	0.15	NA	0.55	NA	0.38	NA	0.29	NA	0.48
12	Reforestation	0.01	0.19	NA	0.11	NA	0.54	NA	0.03	NA	0.80	NA	0.55
13	Maize	0.33	0.27	NA	-0.01	NA	NA	NA	NA	NA	NA	NA	NA
14	Maize	-0.30	0.09	NA	0.12	NA	-0.04	NA	0.25	NA	0.87	NA	0.66
15	Maize	0.02	0.06	NA	0.06	NA	NA	NA	0.30	NA	1.00	NA	0.20
16	Reforestation	0.08	0.48	NA	0.00	NA	-0.10	NA	0.27	NA	0.21	NA	-0.05
17	Reforestation	-0.12	0.67	NA	-0.11	NA	NA	NA	NA	NA	NA	NA	NA
18	Reforestation	0.49	0.71	NA	-0.09	NA	0.01	NA	-0.05	NA	0.48	NA	0.41
19	Reforestation	-0.33	0.71	NA	-0.55	NA	NA	NA	NA	NA	NA	NA	NA
20	Reforestation	0.21	0.64	NA	-0.21	NA	0.11	NA	0.35	NA	0.33	NA	0.33
21	Maize	-0.12	0.16	NA	-0.65	NA	0.59	NA	-0.04	NA	0.29	NA	-0.13
22	Maize	-0.11	0.41	NA	0.07	NA	NA	NA	NA	NA	NA	NA	NA
23	Maize	0.11	0.29	NA	0.08	NA	-0.26	NA	NA	NA	0.04	NA	0.61
24	Maize	-0.18	0.27	NA	-0.11	NA	NA	NA	NA	NA	NA	NA	NA
25	Maize	-0.01	-0.10	NA	-0.11	NA	0.24	NA	1.35	NA	0.64	NA	0.09
26	Reforestation	-0.35	0.12	NA	-0.53	NA	0.36	NA	-0.34	NA	0.14	NA	-0.50
27	Reforestation	-0.04	0.62	NA	-0.15	NA	0.43	NA	0.96	NA	-0.15	NA	0.40
28	Reforestation	0.14	0.76	NA	-0.09	NA	NA	NA	NA	NA	NA	NA	NA
29	Maize	-0.05	-0.19	NA	0.09	NA	0.24	NA	0.26	NA	0.13	NA	0.03
30	Maize	0.08	-0.40	NA	0.00	NA	0.20	NA	0.21	NA	0.08	NA	-0.31
31	Reforestation	0.07	0.39	NA	-0.09	NA	0.69	NA	-0.23	NA	0.24	NA	0.41
32	Reforestation	0.19	0.35	NA	0.04	NA	NA	NA	NA	NA	NA	NA	NA
33	Reforestation	0.16	-0.20	NA	-0.01	NA	0.26	NA	-0.13	NA	0.23	NA	0.46
34	Reforestation	0.09	0.51	NA	0.03	NA	NA	NA	NA	NA	NA	NA	NA
35	Reforestation	0.22	1.70	NA	-0.13	NA	0.08	NA	0.39	NA	0.83	NA	0.31
36	Maize	0.09	0.44	NA	0.05	NA	-0.15	NA	0.37	NA	0.10	NA	0.13
37	Maize	-0.07	0.49	NA	0.02	NA	NA	NA	NA	NA	NA	NA	NA
38	Maize	0.32	0.46	NA	-0.25	NA	0.30	NA	0.16	NA	0.25	NA	0.05
39	Maize	0.05	0.37	NA	-0.13	NA	NA	NA	NA	NA	NA	NA	NA
40	Maize	0.16	0.27	NA	0.12	NA	0.40	NA	0.34	NA	0.52	NA	0.49
41	Reforestation	-0.01	0.17	NA	-0.05	NA	0.66	NA	-0.03	NA	0.52	NA	0.33
42	Reforestation	0.29	0.71	NA	-0.34	NA	0.35	NA	0.54	NA	0.15	NA	-0.04
43	Reforestation	0.31	0.38	NA	0.02	NA	NA	NA	NA	NA	NA	NA	NA
44	Maize	0.02	0.31	NA	-0.03	NA	0.37	NA	0.25	NA	0.13	NA	-0.25
45	Maize	0.13	0.36	NA	0.00	NA	0.23	NA	0.04	NA	0.19	NA	-0.01
Reforest	Mean	0.08	0.51	NA	-0.07	NA	0.36	NA	0.21	NA	0.32	NA	0.26
	SD	0.21	0.36	NA	0.20	NA	0.28	NA	0.34	NA	0.26	NA	0.28
	STD error	0.04	0.08	NA	0.04	NA	0.07	NA	0.09	NA	0.07	NA	0.07
Maize	Mean	0.03	0.19	NA	-0.02	NA	0.23	NA	0.26	NA	0.34	NA	0.15
	SD	0.15	0.23	NA	0.17	NA	0.27	NA	0.37	NA	0.31	NA	0.30
	STD error	0.03	0.05	NA	0.04	NA	0.08	NA	0.10	NA	0.08	NA	0.08

Nitrification (mg NO_3^-N kg^{-1} h^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	0.0163	0.0159	NA	0.0207	NA	0.0403	NA	0.0116	NA	0.0228	NA	0.0204
2	Reforestation	0.0020	0.0286	NA	0.0127	NA	NA	NA	NA	NA	NA	NA	NA
3	Reforestation	NA	0.0461	NA	0.0120	NA	0.0135	NA	0.0252	NA	0.0130	NA	0.0093
4	Reforestation	0.0127	0.0380	NA	0.0118	NA	NA	NA	NA	NA	NA	NA	NA
5	Reforestation	0.0045	0.0190	NA	0.0079	NA	0.0244	NA	0.0182	NA	0.0215	NA	0.0222
6	Maize	NA	0.0004	NA	0.0072	NA	0.0111	NA	0.0089	NA	NA	NA	0.0129
7	Maize	0.0038	0.0003	NA	0.0089	NA	NA	NA	NA	NA	NA	NA	NA
8	Maize	0.0039	0.0132	NA	0.0110	NA	0.0186	NA	0.0095	NA	0.0097	NA	0.0133
9	Maize	NA	0.0083	NA	0.0082	NA	NA	NA	NA	NA	NA	NA	NA
10	Maize	0.0026	0.0131	NA	0.0065	NA	0.0335	NA	NA	NA	0.0286	NA	0.0178
11	Reforestation	0.0036	0.0164	NA	0.0057	NA	0.0241	NA	0.0175	NA	0.0170	NA	0.0245
12	Reforestation	NA	0.0129	NA	0.0066	NA	0.0263	NA	0.0059	NA	0.0419	NA	0.0297
13	Maize	0.0192	0.0165	NA	0.0064	NA	NA	NA	NA	NA	NA	NA	NA
14	Maize	NA	0.0099	NA	0.0069	NA	0.0082	NA	0.0131	NA	0.0424	NA	0.0232
15	Maize	0.0015	0.0083	NA	0.0074	NA	0.0177	NA	0.0147	NA	0.0475	NA	NA
16	Reforestation	0.0023	0.0302	NA	0.0068	NA	0.0080	NA	0.0168	NA	0.0135	NA	0.0041
17	Reforestation	NA	0.0393	NA	0.0085	NA	NA	NA	NA	NA	NA	NA	NA
18	Reforestation	NA	0.0402	NA	0.0076	NA	0.0070	NA	0.0044	NA	0.0267	NA	0.0188
19	Reforestation	NA	0.0314	NA	0.0072	NA	NA	NA	NA	NA	NA	NA	NA
20	Reforestation	0.0089	0.0293	NA	0.0088	NA	0.0141	NA	0.0242	NA	0.0207	NA	0.0214
21	Maize	NA	0.0124	NA	0.0058	NA	0.0244	NA	0.0030	NA	0.0166	NA	NA
22	Maize	NA	0.0215	NA	0.0066	NA	NA	NA	NA	NA	NA	NA	NA
23	Maize	0.0040	0.0156	NA	0.0067	NA	NA	NA	NA	NA	0.0035	NA	0.0255
24	Maize	NA	0.0137	NA	0.0056	NA	NA	NA	NA	NA	NA	NA	NA
25	Maize	0.0031	0.0043	NA	0.0077	NA	0.0134	NA	NA	NA	0.0324	NA	0.0114
26	Reforestation	NA	0.0133	NA	0.0064	NA	0.0230	NA	NA	NA	0.0094	NA	NA
27	Reforestation	0.0194	0.0300	NA	0.0070	NA	0.0271	NA	0.0454	NA	0.0102	NA	0.0207
28	Reforestation	0.0093	0.0357	NA	0.0091	NA	NA	NA	NA	NA	NA	NA	NA
29	Maize	NA	NA	NA	0.0051	NA	0.0189	NA	0.0122	NA	0.0092	NA	0.0095
30	Maize	0.0039	NA	NA	0.0068	NA	0.0112	NA	0.0130	NA	0.0090	NA	0.0032
31	Reforest	0.0036	0.0220	NA	0.0081	NA	0.0355	NA	0.0424	NA	0.0131	NA	0.0126
32	Reforest	0.0137	0.0278	NA	0.0068	NA	NA	NA	NA	NA	NA	NA	NA
33	Reforest	0.0066	NA	NA	0.0069	NA	0.0150	NA	0.0049	NA	0.0157	NA	0.0199
34	Reforest	0.0029	0.0272	NA	0.0061	NA	NA	NA	NA	NA	NA	NA	NA
35	Reforest	0.0113	0.0786	NA	0.0089	NA	0.0107	NA	0.0150	NA	0.0500	NA	0.0161
36	Maize	0.0077	0.0222	NA	0.0067	NA	0.0010	NA	0.0183	NA	0.0099	NA	NA
37	Maize	NA	0.0244	NA	0.0065	NA	NA	NA	NA	NA	NA	NA	NA
38	Maize	0.0201	0.0256	NA	0.0061	NA	0.0190	NA	0.0120	NA	0.0183	NA	0.0047
39	Maize	0.0012	0.0203	NA	0.0064	NA	NA	NA	NA	NA	NA	NA	NA
40	Maize	0.0072	0.0160	NA	0.0079	NA	0.0209	NA	0.0141	NA	0.0262	NA	0.0183
41	Reforestation	0.0069	0.0121	NA	0.0052	NA	0.0295	NA	0.0063	NA	0.0307	NA	NA
42	Reforestation	0.0157	0.0405	NA	0.0096	NA	0.0146	NA	0.0272	NA	0.0131	NA	0.0059
43	Reforestation	0.0205	0.0284	NA	0.0092	NA	NA	NA	NA	NA	NA	NA	NA
44	Maize	0.0062	0.0178	NA	0.0055	NA	0.0195	NA	0.0131	NA	0.0125	NA	NA
45	Maize	0.0068	0.0218	NA	0.0074	NA	0.0131	NA	0.0063	NA	0.0139	NA	0.0020
Reforest	Mean	0.0094	0.0301	NA	0.0087	NA	0.0209	NA	0.0189	NA	0.0213	NA	0.0174
	SD	0.0061	0.0146	NA	0.0033	NA	0.0100	NA	0.0130	NA	0.0118	NA	0.0075
	STD error	0.0015	0.0031	NA	0.0007	NA	0.0026	NA	0.0035	NA	0.0030	NA	0.0021
Maize	Mean	0.0065	0.0143	NA	0.0070	NA	0.0165	NA	0.0115	NA	0.0200	NA	0.0129
	SD	0.0059	0.0074	NA	0.0013	NA	0.0078	NA	0.0040	NA	0.0134	NA	0.0078
	STD error	0.0016	0.0017	NA	0.0003	NA	0.0021	NA	0.0012	NA	0.0036	NA	0.0024

Microbial biomass carbon (mg C kg^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	1632.54	1549.34	1092.96	1166.35	1200.15	533.07	681.60	799.71	503.61	481.01	425.52	310.53
2	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
3	Reforestation	899.09	1827.11	NA	724.02	999.63	819.35	890.78	1183.09	900.72	842.64	657.01	579.92
4	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
5	Reforestation	1093.15	1407.46	1121.15	834.84	895.20	259.70	870.03	215.64	771.62	338.73	612.67	517.58
6	Maize	791.46	1116.33	566.78	649.86	590.13	206.53	177.44	165.42	132.28	223.17	213.47	181.48
7	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
8	Maize	792.03	1038.22	881.92	869.64	908.25	479.27	599.76	575.02	559.30	556.59	583.55	605.55
9	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
10	Maize	942.94	460.19	865.65	578.73	945.26	501.84	758.66	721.30	667.72	425.27	459.05	245.91
11	Reforestation	483.89	1100.32	453.80	142.68	613.47	629.83	497.38	293.14	339.18	579.24	432.41	209.15
12	Reforestation	548.40	1077.61	1017.35	NA	883.43	652.12	523.60	245.65	615.55	311.83	328.21	436.99
13	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14	Maize	936.74	1205.82	1027.25	752.29	917.48	281.10	641.45	831.75	514.84	523.13	511.29	449.24
15	Maize	978.02	1169.72	1412.56	905.47	961.18	673.64	861.11	937.38	636.29	693.44	654.45	533.63
16	Reforestation	117.42	1264.46	1912.21	579.97	1193.20	518.91	569.79	776.47	836.63	395.01	438.30	486.66
17	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
18	Reforestation	838.06	1420.76	1245.82	442.16	885.37	458.44	487.48	947.18	766.51	485.88	357.07	358.68
19	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
20	Reforestation	567.83	1257.76	1787.97	451.83	786.92	637.71	583.35	784.83	778.71	733.70	672.70	537.87
21	Maize	619.87	977.33	721.01	280.03	909.81	257.67	313.31	163.45	454.50	418.28	317.91	310.18
22	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
23	Maize	687.94	905.76	704.90	488.44	865.09	141.18	314.25	287.96	401.55	574.49	436.97	432.49
24	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
25	Maize	765.43	1040.67	724.95	543.56	1008.98	408.42	361.16	264.38	493.76	528.36	325.92	197.08
26	Reforestation	364.99	1255.30	1191.52	691.08	734.21	480.08	805.79	540.30	272.37	402.25	368.55	311.98
27	Reforestation	1337.47	848.44	1258.00	1054.97	748.53	713.69	935.99	748.72	893.45	766.99	724.00	821.17
28	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
29	Maize	626.80	969.55	1100.78	398.33	729.41	565.48	582.56	302.81	529.74	341.96	312.61	192.27
30	Maize	544.15	1230.04	594.69	574.47	1104.67	486.61	622.20	672.53	748.10	365.11	298.99	159.91
31	Reforestation	760.58	1001.47	1688.50	435.50	770.97	641.12	803.65	518.50	1208.72	533.80	526.10	542.55
32	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
33	Reforestation	774.32	1282.93	1323.95		1067.03	612.92	385.10	668.09	746.56	578.92	508.73	346.64
34	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
35	Reforestation	805.78	1806.34	1469.51	494.43	866.64	507.25	470.37	301.77	503.66	643.66	434.50	288.75
36	Maize	650.09	887.62	777.58	314.10	1054.27	527.40	632.31	367.32	995.73	482.11	393.67	329.96
37	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
38	Maize	934.99	844.72	1262.48	429.53	1141.54	496.83	541.82	371.94	986.29	292.55	316.12	313.66
39	Maize	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
40	Maize	992.86	847.08	966.69	304.59	1039.48	300.31	672.19	350.13	1153.45	514.94	507.74	463.69
41	Reforestation	658.34	748.87	769.58	718.83	1034.08	595.61	587.46	1123.81	681.47	957.45	627.10	462.58
42	Reforestation	1364.70	1588.00	1516.24	850.91	943.22	655.72	865.56	924.70	759.88	603.56	528.24	514.43
43	Reforestation	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
44	Maize	1104.47	989.25	997.11	738.32	1014.27	582.75	728.67	575.97	946.50	495.65	448.27	373.56
45	Maize	980.76	995.98	1190.71	NA	1117.15	589.40	695.87	513.73	779.57	595.75	526.98	337.62

Reforest	Mean	816.44	1295.74	1274.90	660.58	908.14	581.03	663.86	671.44	705.24	576.98	509.41	448.36
	SD	404.32	315.85	392.20	278.47	168.25	129.71	181.96	311.94	235.12	187.32	125.12	151.85
	STD error	104.39	81.55	104.82	77.23	43.44	33.49	46.98	80.54	60.71	48.37	32.31	39.21

Maize	Mean	823.24	978.55	919.67	559.10	953.80	433.23	566.85	473.41	666.64	468.72	420.47	341.75
	SD	170.67	188.19	248.52	204.80	147.54	158.91	191.65	239.36	271.25	124.69	122.88	135.02
	STD error	44.07	48.59	64.17	54.74	38.10	41.03	49.48	61.80	70.04	32.20	31.73	34.86

Dissolved organic carbon (mg C kg^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	76.66	71.59	67.61	70.91	77.10	44.32	69.73	27.42	59.47	52.63	54.78	52.38
2	Reforestation	42.33	51.13	59.00	102.23	43.20	39.43	47.77	59.01	45.74	41.54	52.40	69.10
3	Reforestation	34.34	74.08	102.87	65.88	60.08	53.51	55.18	50.83	34.20	34.15	81.31	42.31
4	Reforestation	35.79	42.01	50.67	79.33	75.18	66.32	26.04	42.78	35.57	48.15	36.38	45.44
5	Reforestation	43.59	29.98	62.13	69.61	46.65	40.88	43.67	NA	38.37	54.54	60.65	56.70
6	Maize	17.84	55.80	42.70	61.43	20.14	20.46	26.47	33.66	34.58	44.87	92.77	46.76
7	Maize	24.01	24.41	55.60	70.09	32.91	13.46	25.54	32.49	29.36	31.24	51.42	41.30
8	Maize	26.96	53.78	68.13	61.29	26.41	34.91	31.67	30.36	32.04	31.53	101.02	46.81
9	Maize	22.29	38.36	65.00	42.93	36.30	40.30	24.92	29.72	31.95	39.56	27.67	42.56
10	Maize	25.00	41.79	49.39	68.44	33.51	45.52	51.67	35.65	43.23	31.24	83.66	47.96
11	Reforestation	29.49	55.85	35.09	51.64	50.84	34.94	30.29	33.38	26.77	28.53	71.96	55.82
12	Reforestation	26.15	60.21	73.13	56.95	46.32	31.57	31.32	39.29	30.03	33.12	104.91	34.06
13	Maize	30.76	27.05	36.85	36.70	32.67	31.74	31.80	37.82	26.52	22.06	30.73	44.63
14	Maize	40.84	40.68	58.63	61.37	11.05	31.61	30.32	41.52	20.97	23.58	47.60	43.18
15	Maize	22.56	57.25	61.66	44.22	19.17	29.27	24.00	46.04	59.19	33.14	33.87	56.31
16	Reforestation	57.43	49.84	36.59	128.40	31.36	23.72	19.74	43.58	21.52	24.67	73.68	37.89
17	Reforestation	31.38	65.43	37.80	48.62	44.16	46.25	29.11	38.16	46.34	40.95	28.60	49.71
18	Reforestation	73.95	54.39	37.00	105.32	18.04	30.51	68.39	47.94	22.69	39.95	55.30	37.68
19	Reforestation	29.77	69.85	67.91	73.89	38.41	81.05	27.59	43.63	42.86	54.01	51.73	42.41
20	Reforestation	65.28	46.61	85.79	113.89	29.94	14.01	27.39	43.30	22.05	33.13	75.08	40.45
21	Maize	28.78	27.96	34.95	108.32	15.29	20.66	32.57	36.28	32.96	29.30	78.60	36.39
22	Maize	22.07	32.68	51.36	44.77	42.94	42.72	31.61	25.99	30.61	42.41	50.54	55.93
23	Maize	29.46	29.06	49.85	103.14	21.12	47.02	49.99	50.89	30.55	27.59	56.68	30.38
24	Maize	32.41	38.37	35.62	63.87	38.30	25.68	23.71	59.54	25.60	37.23	65.76	31.19
25	Maize	42.57	48.60	50.50	104.20	30.15	25.66	30.16	45.64	23.21	23.95	71.90	37.90
26	Reforestation	24.62	90.27	34.59	148.33	16.34	25.50	29.81	38.36	9.49	20.55	33.59	27.17
27	Reforestation	23.69	43.98	63.66	140.40	22.48	48.88	48.05	35.85	10.46	20.90	51.42	51.18
28	Reforestation	25.51	54.99	50.79	65.78	41.99	40.64	33.96	59.73	10.68	12.48	69.55	67.62
29	Maize	10.13	37.18	44.88	132.43	18.64	24.29	36.84	44.36	11.22	22.74	71.03	67.02
30	Maize	21.47	48.27	36.82	135.87	22.79	36.58	31.51	31.95	11.60	21.33	61.61	73.64
31	Reforestation	18.32	51.13	36.49	96.87	42.62	37.86	12.39	30.97	10.37	24.12	87.25	22.10
32	Reforestation	38.03	68.07	50.43	43.78	30.72	34.63	61.03	38.95	38.77	53.73	48.61	30.42
33	Reforestation	20.77	77.78	48.05	95.54	16.44	49.47	49.29	26.51	32.99	39.79	41.95	29.79
34	Reforestation	17.51	47.60	51.68	36.91	42.82	21.41	33.62	28.64	46.48	35.30	50.01	29.64
35	Reforestation	27.23	89.82	59.63	129.38	7.33	26.52	33.91	28.07	25.01	40.76	30.06	33.16
36	Maize	28.52	34.74	44.47	97.38	2.23	59.08	16.95	12.74	23.55	39.28	22.58	32.14
37	Maize	30.56	35.89	47.86	36.45	34.09	93.17	44.28	28.45	45.11	38.31	45.34	32.63
38	Maize	52.78	36.75	45.53	119.63	17.18	32.13	32.49	32.60	28.79	29.09	58.66	39.15
39	Maize	57.85	27.21	43.68	41.41	40.80	33.68	25.49	29.27	36.60	38.59	30.62	34.70
40	Maize	27.11	38.43	39.71	97.83	21.40	30.96	21.63	27.77	25.57	24.44	35.78	28.90
41	Reforestation	33.79	38.20	46.24	121.65	40.60	54.65	29.60	47.55	22.86	22.60	62.79	41.60
42	Reforestation	38.16	40.43	43.59	120.98	15.61	52.26	40.23	58.14	18.01	20.17	48.82	48.26
43	Reforestation	33.34	37.33	43.44	41.51	43.88	27.75	23.68	38.85	34.29	43.94	28.11	45.88
44	Maize	43.19	40.85	44.91	128.77	27.83	54.91	38.40	31.01	26.94	21.11	26.92	50.55
45	Maize	64.82	37.00	30.74	113.31	27.54	36.57	22.45	31.67	26.49	23.58	38.26	46.79

Reforest	Mean	36.83	56.98	54.10	87.30	38.35	40.26	37.90	40.95	29.78	35.64	56.48	43.08
	SD	16.61	16.46	17.33	34.18	17.90	15.37	15.15	10.01	13.52	12.38	19.85	12.28
	STD error	3.46	3.43	3.61	7.13	3.73	3.21	3.16	2.13	2.82	2.58	4.14	2.56

Maize	Mean	31.91	38.73	47.22	80.63	26.02	36.84	31.11	35.25	29.85	30.73	53.77	43.95
	SD	13.38	9.31	9.96	33.91	10.17	16.74	8.83	9.84	10.40	7.49	22.53	11.64
	STD error	2.85	1.99	2.12	7.23	2.17	3.57	1.88	2.10	2.22	1.60	4.80	2.48

Total carbon (%)

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	3.09	2.39	2.58	3.04	1.70	1.95	1.77	1.84	1.58	2.38	2.02	2.02
2	Reforestation	1.71	2.50	2.12	2.72	1.78	1.90	2.32	1.76	1.92	3.18	1.79	2.13
3	Reforestation	1.76	1.96	2.96	2.03	1.72	1.70	2.19	2.06	2.01	2.15	2.05	1.81
4	Reforestation	1.62	1.56	1.90	2.66	1.79	1.93	1.79	1.76	1.84	1.76	1.92	2.43
5	Reforestation	1.71	1.53	2.42	1.71	1.71	1.90	1.75	1.74	2.05	2.14	1.85	2.14
6	Maize	1.12	1.53	0.94	1.57	0.99	0.95	1.08	1.06	1.07	1.11	1.15	1.34
7	Maize	1.09	1.09	1.10	1.64	1.25	1.38	1.15	1.15	1.19	1.22	1.31	1.35
8	Maize	1.15	1.20	1.44	1.97	1.57	1.58	1.41	1.30	1.62	1.43	1.42	1.54
9	Maize	1.22	1.14	1.31	1.52	1.23	1.39	1.32	1.41	1.41	1.38	1.35	1.53
10	Maize	1.37	0.98	1.65	1.70	1.58	1.58	1.42	1.73	1.64	1.58	1.62	1.71
11	Reforestation	1.39	1.52	1.42	1.34	1.55	1.41	1.44	1.47	1.51	1.70	1.74	1.58
12	Reforestation	1.36	1.46	1.63	1.17	2.14	1.69	1.52	1.55	1.49	1.74	1.78	1.72
13	Maize	1.63	1.37	1.60	1.58	1.67	1.93	1.67	1.58	1.58	1.95	1.64	2.08
14	Maize	1.46	1.35	1.70	1.40	1.54	1.46	1.65	1.61	1.27	1.55	1.62	1.73
15	Maize	1.42	1.26	1.74	1.63	1.66	1.64	1.73	1.68	1.75	1.73	1.71	1.83
16	Reforestation	1.04	1.75	2.50	2.00	1.93	1.31	1.40	1.54	1.56	1.44	1.66	1.65
17	Reforestation	1.10	1.77	1.49	1.96	1.57	1.49	1.51	1.41	1.58	1.60	1.66	1.72
18	Reforestation	1.47	1.77	1.95	1.73	1.40	1.26	1.51	1.61	1.44	1.85	1.26	1.69
19	Reforestation	1.53	2.69	3.14	2.12	1.81	1.89	1.69	1.90	1.41	1.81	1.70	1.68
20	Reforestation	1.47	1.97	2.42	1.65	1.53	1.78	1.24	1.65	1.57	2.21	1.69	1.74
21	Maize	1.19	1.29	1.36	1.51	1.43	1.24	1.10	1.17	1.40	1.56	1.49	1.58
22	Maize	1.41	1.34	1.39	1.52	1.47	1.33	1.37	1.41	1.54	1.49	1.45	1.55
23	Maize	1.40	1.44	1.58	1.52	1.43	1.42	1.36	1.37	1.55	1.39	1.50	1.64
24	Maize	1.51	1.43	1.61	1.68	1.70	1.31	1.19	1.46	1.30	1.49	1.38	1.44
25	Maize	1.58	1.54	1.65	1.75	1.68	1.45	0.93	1.65	1.48	1.63	1.59	1.67
26	Reforestation	1.19	1.91	1.26	1.74	1.42	1.12	1.27	1.51	1.07	1.25	1.38	1.34
27	Reforestation	1.90	1.69	2.00	1.65	1.12	1.42	1.55	2.04	1.70	1.73	1.50	1.70
28	Reforestation	1.70	2.02	2.13	2.68	2.16	1.43	1.72	1.93	1.43	2.02	2.08	1.60
29	Maize	1.12	1.17	1.40	1.49	1.34	1.48	1.21	1.29	1.22	1.39	1.44	1.51
30	Maize	1.08	1.30	1.21	1.79	1.67	1.27	1.57	1.54	1.51	1.49	1.70	1.49
31	Reforestation	1.74	1.46	1.47	1.75	1.51	1.40	1.35	1.82	1.80	1.51	2.66	2.19
32	Reforestation	1.16	2.39	2.14	1.73	1.30	1.74	2.21	1.61	2.14	1.46	2.20	1.91
33	Reforestation	1.17	1.75	1.99	1.53	1.25	1.83	1.34	1.63	1.12	1.75	2.18	1.82
34	Reforestation	1.32	2.03	1.77	1.43	1.54	1.20	1.30	1.43	1.33	1.72	2.73	1.68
35	Reforestation	1.32	2.45	2.62	1.98	1.36	1.51	1.41	1.57	1.44	2.30	1.73	1.82
36	Maize	1.57	1.42	1.41	1.48	1.60	1.58	1.61	1.61	1.58	1.57	1.73	1.53
37	Maize	1.37	1.46	1.52	1.66	1.60	1.54	1.61	1.68	1.63	1.68	1.70	1.57
38	Maize	1.48	1.43	1.71	1.48	1.62	1.42	1.27	1.60	1.58	1.61	1.68	1.65
39	Maize	1.33	1.38	1.63	1.58	1.55	1.38	1.53	1.55	1.46	1.76	1.59	1.73
40	Maize	1.56	1.30	1.51	1.65	1.53	1.46	1.53	1.46	1.65	1.63	1.57	1.73
41	Reforestation	1.67	1.40	1.40	1.59	1.74	2.05	1.92	1.96	1.68	1.87	1.92	1.84
42	Reforestation	1.59	2.39	2.21	2.33	1.81	1.78	2.04	1.90	1.61	1.79	1.73	1.89
43	Reforestation	1.72	1.94	2.16	1.97	1.94	1.61	1.69	1.73	1.69	1.79	1.63	2.28
44	Maize	1.69	1.61	1.76	1.77	1.64	1.65	1.69	1.59	1.34	1.52	1.64	1.67
45	Maize	1.83	1.53	1.61	1.68	1.66	1.69	1.67	1.50	1.47	1.64	1.57	1.61

Reforest	Mean	1.553	1.926	2.073	1.935	1.642	1.622	1.650	1.713	1.607	1.876	1.863	1.843
	SD	0.415	0.381	0.501	0.475	0.269	0.269	0.315	0.192	0.270	0.399	0.350	0.254
	STD error	0.086	0.079	0.105	0.099	0.056	0.056	0.066	0.040	0.056	0.083	0.073	0.053

Maize	Mean	1.388	1.342	1.491	1.617	1.519	1.460	1.412	1.472	1.465	1.536	1.538	1.612
	SD	0.210	0.157	0.214	0.131	0.179	0.195	0.233	0.185	0.173	0.180	0.152	0.162
	STD error	0.045	0.034	0.046	0.028	0.038	0.042	0.050	0.039	0.037	0.038	0.032	0.034

Total nitrogen (%)

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	0.2577	0.1809	0.2472	0.2672	0.1436	0.1525	0.1658	0.1320	0.1370	0.2205	0.1887	0.1820
2	Reforestation	0.1159	0.2042	0.1891	0.2239	0.1361	0.1570	0.2084	0.1438	0.1748	0.2973	0.1651	0.1827
3	Reforestation	0.1104	0.1365	0.2545	0.1742	0.1230	0.1368	0.1832	0.1698	0.1869	0.1944	0.1802	0.1560
4	Reforestation	0.0999	0.0861	0.1748	0.2411	0.1377	0.1519	0.1653	0.1487	0.1694	0.1563	0.1714	0.2149
5	Reforestation	0.1019	0.0850	0.2135	0.1625	0.1256	0.1118	0.1550	0.1493	0.1823	0.1869	0.1691	0.1844
6	Maize	NA	0.1019	0.0732	0.1150	0.0410	0.0437	0.0562	0.0626	0.0617	0.0550	0.0712	0.0818
7	Maize	0.0162	0.0421	0.0707	0.1156	0.0548	0.0703	0.0571	0.0849	0.0776	0.0828	0.0720	0.0854
8	Maize	0.0443	0.0349	0.0845	0.1513	0.0936	0.0787	0.1130	0.1026	0.1028	0.1007	0.0986	0.1123
9	Maize	0.0270	0.0071	0.0879	0.1187	0.0692	0.0878	0.0930	0.0957	0.0822	0.0866	0.0983	0.1151
10	Maize	0.0522	NA	0.1107	0.1163	0.1051	0.1020	0.1123	0.1307	0.1057	0.1270	0.1351	0.1313
11	Reforestation	0.0399	0.0816	0.1088	0.0540	0.0961	0.1120	0.1067	0.0998	0.1068	0.1247	0.1107	0.1159
12	Reforestation	0.0477	0.0681	0.1225	0.0712	0.1685	0.1359	0.1150	0.1146	0.1162	0.1446	0.1564	0.1420
13	Maize	0.0738	0.0560	0.1013	0.0922	0.1253	0.1361	0.1227	0.1201	0.1050	0.1613	0.1390	0.1796
14	Maize	0.0572	0.0512	0.1076	0.0783	0.0894	0.0913	0.1036	0.1150	0.0971	0.1242	0.1378	0.1292
15	Maize	0.0613	0.0372	0.1055	0.1095	0.1176	0.1045	0.1253	0.1312	0.1375	0.1370	0.1524	0.1569
16	Reforestation	NA	0.0785	0.1882	0.1550	0.1290	0.0685	0.0930	0.1017	0.1033	0.0965	0.1247	0.1256
17	Reforestation	0.0201	0.0956	0.1033	0.1362	0.1050	0.0948	0.0954	0.0888	0.1076	0.1328	0.1097	0.1275
18	Reforestation	0.0701	0.0914	0.1322	0.1063	0.0643	0.0864	0.1062	0.1135	0.1110	0.1514	0.0960	0.1244
19	Reforestation	0.0772	0.1767	0.2594	0.1503	0.1262	0.1380	0.1285	0.1421	0.1174	0.1557	0.1295	0.1183
20	Reforestation	0.0548	0.0915	0.1872	0.1079	0.1141	0.1350	0.0807	0.1461	0.1268	0.1955	0.1474	0.1453
21	Maize	0.0156	0.0374	0.0855	0.0866	0.1816	0.0818	0.0566	0.0770	0.1069	0.1150	0.1146	0.1134
22	Maize	0.0367	0.0373	0.0910	0.0635	0.0843	0.0708	0.0915	0.0920	0.1086	0.1142	0.1176	0.1231
23	Maize	0.0429	0.0439	0.1067	0.1053	0.0851	0.0983	0.1073	0.0957	0.1088	0.0985	0.1179	0.1295
24	Maize	0.0608	0.0633	0.1102	0.1000	0.1011	0.0734	0.0750	0.0885	0.0991	0.0813	0.0951	0.1062
25	Maize	0.0774	0.0756	0.1160	0.1283	0.1065	0.0745	0.0446	0.1206	0.1058	0.1257	0.1293	0.1204
26	Reforestation	0.0281	0.0826	0.0830	0.1313	0.0682	0.0330	0.0787	0.0909	0.0560	0.0853	0.0794	0.0753
27	Reforestation	0.1213	0.0923	0.1545	0.1096	0.0706	0.0780	0.1073	0.1603	0.1365	0.1400	0.1014	0.1127
28	Reforestation	0.0904	0.1275	0.1682	0.2209	0.1498	0.0828	0.1348	0.1657	0.1265	0.1790	0.1866	0.1129
29	Maize	0.0127	0.0432	0.0891	0.0836	0.0526	0.1008	0.0744	0.0776	0.0934	0.0933	0.0626	0.1023
30	Maize	0.0139	0.0257	0.0828	0.1201	0.0921	0.0594	0.0948	0.1034	0.1089	0.1210	0.1172	0.1007
31	Reforestation	0.1130	0.0550	0.0860	0.1150	0.0791	0.0788	0.0849	0.1245	0.1404	0.1068	0.2317	0.1886
32	Reforestation	0.0093	0.1649	0.1887	0.1107	0.0833	0.1227	0.1837	0.1036	0.1777	0.1045	0.1918	0.1344
33	Reforestation	0.0079	0.0938	0.1474	0.0856	0.0803	0.1296	0.0787	0.1171	0.0722	0.1475	0.1500	0.1359
34	Reforestation	0.0281	0.1159	0.1141	0.0860	0.1059	0.0639	0.0673	0.0736	0.1060	0.1183	0.2077	0.1219
35	Reforestation	0.0395	0.1450	0.2148	0.1322	0.0791	0.0895	0.1051	0.0987	0.1079	0.1854	0.1226	0.1460
36	Maize	0.0523	0.0559	0.1023	0.0892	0.0826	0.0926	0.1053	0.1021	0.1125	0.1110	0.1180	0.0937
37	Maize	0.0447	0.0590	0.1129	0.0986	0.0968	0.0916	0.1091	0.1087	0.1172	0.1245	0.0888	0.1087
38	Maize	0.0515	0.0448	0.1025	0.1036	0.0941	0.0989	0.0826	0.1020	0.1098	0.1158	0.1021	0.1224
39	Maize	0.0369	0.0502	0.1071	0.1020	0.0983	0.0829	0.1056	0.1080	0.1135	0.1301	0.1177	0.1288
40	Maize	0.0472	0.0517	0.0973	0.1011	0.1027	0.1013	0.1012	0.1014	0.1253	0.1200	0.1482	0.1242
41	Reforestation	0.0707	0.0358	0.0990	0.1008	0.1079	0.1361	0.1398	0.1531	0.1368	0.1464	0.1424	0.1489
42	Reforestation	0.0564	0.1420	0.1645	0.1831	0.1063	0.1323	0.1536	0.1471	0.1269	0.1333	0.1551	0.1406
43	Reforestation	0.0728	0.1149	0.1691	0.1433	0.1392	0.1003	0.1104	0.1195	0.1201	0.1393	0.1097	0.1902
44	Maize	0.0873	0.0616	0.1255	0.1233	0.1154	0.1110	0.1103	0.0980	0.1006	0.1005	0.1159	0.1059
45	Maize	0.1201	0.0737	0.1273	0.1194	0.1095	0.0862	0.1107	0.1035	0.1041	0.0936	0.1041	0.1161
Reforest	Mean	0.0742	0.1107	0.1639	0.1421	0.1104	0.1099	0.1238	0.1263	0.1281	0.1540	0.1490	0.1446
	SD	0.0542	0.0427	0.0526	0.0556	0.0291	0.0331	0.0392	0.0272	0.0333	0.0464	0.0390	0.0328
	STD error	0.0116	0.0089	0.0110	0.0116	0.0061	0.0069	0.0082	0.0057	0.0070	0.0097	0.0081	0.0068
Maize	Mean	0.0491	0.0502	0.0999	0.1055	0.0954	0.0881	0.0933	0.1010	0.1038	0.1100	0.1115	0.1176
	SD	0.0264	0.0196	0.0153	0.0192	0.0287	0.0193	0.0233	0.0169	0.0157	0.0229	0.0243	0.0217
	STD error	0.0058	0.0043	0.0033	0.0041	0.0061	0.0041	0.0050	0.0036	0.0034	0.0049	0.0052	0.0046

C : N Ratio

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	12.01	13.22	10.42	11.36	11.82	12.81	10.66	13.92	11.53	10.79	10.71	11.10
2	Reforestation	14.73	12.23	11.18	12.13	13.06	12.07	11.15	12.21	10.98	10.68	10.84	11.66
3	Reforestation	15.91	14.35	11.64	11.64	13.98	12.46	11.93	12.10	10.74	11.08	11.40	11.62
4	Reforestation	16.21	18.06	10.89	11.03	13.01	12.69	10.83	11.82	10.86	11.27	11.19	11.33
5	Reforestation	16.80	17.96	11.34	10.54	13.61	16.97	11.30	11.65	11.24	11.45	10.96	11.58
6	Maize	NA	14.99	12.80	13.64	24.24	21.76	19.27	16.93	17.34	20.09	16.17	16.42
7	Maize	67.10	25.82	15.59	14.20	22.77	19.59	20.14	13.55	15.32	14.76	18.14	15.75
8	Maize	25.87	34.38	17.01	13.05	16.73	20.01	12.47	12.65	15.73	14.15	14.36	13.68
9	Maize	45.04	NA	14.85	12.81	17.73	15.81	14.16	14.70	17.12	15.97	13.71	13.27
10	Maize	26.28	NA	14.91	14.60	15.06	15.46	12.60	13.25	15.47	12.41	11.97	13.05
11	Reforestation	34.79	18.64	13.07	24.74	16.11	12.59	13.51	14.69	14.14	13.66	15.68	13.59
12	Reforestation	28.55	21.47	13.31	16.43	12.70	12.43	13.22	13.55	12.81	12.04	11.41	12.11
13	Maize	22.05	24.48	15.77	17.15	13.29	14.17	13.63	13.16	15.03	12.08	11.81	11.55
14	Maize	25.47	26.33	15.75	17.92	17.26	15.99	15.94	13.97	13.07	12.51	11.78	13.35
15	Maize	23.20	33.95	16.49	14.90	14.14	15.71	13.81	12.77	12.73	12.62	11.22	11.66
16	Reforestation	NA	22.23	13.27	12.90	14.95	19.09	15.03	15.15	15.14	14.96	13.29	13.16
17	Reforestation	54.63	18.50	14.46	14.35	14.93	15.76	15.81	15.91	14.67	12.02	15.09	13.51
18	Reforestation	21.00	19.38	14.74	16.29	21.76	14.61	14.22	14.16	12.99	12.25	13.10	13.59
19	Reforestation	19.82	15.23	12.12	14.13	14.32	13.72	13.18	13.34	12.03	11.60	13.12	14.23
20	Reforestation	26.81	21.49	12.90	15.26	13.42	13.20	15.32	11.31	12.39	11.29	11.49	11.99
21	Maize	76.54	34.41	15.88	17.38	7.87	15.10	19.35	15.25	13.09	13.55	12.98	13.97
22	Maize	38.28	35.90	15.25	23.92	17.41	18.84	14.98	15.37	14.15	13.01	12.32	12.62
23	Maize	32.59	32.69	14.77	14.47	16.80	14.45	12.67	14.29	14.28	14.09	12.75	12.66
24	Maize	24.77	22.59	14.63	16.82	16.81	17.87	15.85	16.49	13.16	18.38	14.50	13.53
25	Maize	20.37	20.34	14.25	13.64	15.77	19.49	20.75	13.67	14.02	12.94	12.31	13.84
26	Reforestation	42.35	23.15	15.17	13.26	20.82	34.00	16.19	16.64	19.18	14.68	17.43	17.84
27	Reforestation	15.68	18.32	12.95	15.08	15.86	18.14	14.47	12.74	12.47	12.33	14.78	15.04
28	Reforestation	18.78	15.84	12.66	12.14	14.41	17.21	12.77	11.64	11.32	11.31	11.13	14.18
29	Maize	NA	27.13	15.70	17.78	25.55	14.71	16.24	16.59	13.10	14.92	22.94	14.75
30	Maize	NA	50.39	14.59	14.90	18.18	21.31	16.52	14.92	13.88	12.35	14.52	14.78
31	Reforest	15.36	26.62	17.09	15.19	19.10	17.72	15.92	14.58	12.79	14.16	11.47	11.63
32	Reforest	NA	14.50	11.36	15.66	15.58	14.21	12.02	15.57	12.01	14.00	11.49	14.20
33	Reforest	NA	18.70	13.49	17.90	15.59	14.14	17.01	13.91	15.50	11.86	14.56	13.42
34	Reforest	46.87	17.53	15.50	16.66	14.51	18.75	19.33	19.36	12.52	14.50	13.13	13.77
35	Reforest	33.44	16.88	12.22	14.98	17.23	16.89	13.43	15.94	13.31	12.40	14.14	12.45
36	Maize	30.00	25.38	13.77	16.55	19.38	17.03	15.33	15.76	14.05	14.11	14.69	16.30
37	Maize	30.56	24.69	13.47	16.87	16.51	16.83	14.75	15.44	13.91	13.49	19.16	14.45
38	Maize	28.66	31.85	16.71	14.26	17.18	14.36	15.40	15.73	14.41	13.86	16.46	13.44
39	Maize	35.99	27.45	15.25	15.51	15.75	16.69	14.50	14.34	12.89	13.52	13.48	13.42
40	Maize	33.07	25.18	15.49	16.35	14.85	14.39	15.09	14.36	13.14	13.61	10.58	13.96
41	Reforestation	23.62	39.02	14.13	15.74	16.08	15.06	13.75	12.82	12.30	12.77	13.46	12.37
42	Reforestation	28.17	16.85	13.40	12.71	17.04	13.42	13.27	12.90	12.66	13.41	11.17	13.42
43	Reforestation	23.64	16.92	12.77	13.77	13.94	16.09	15.34	14.46	14.10	12.84	14.82	11.97
44	Maize	19.34	26.07	14.03	14.32	14.23	14.87	15.36	16.26	13.29	15.14	14.17	15.80
45	Maize	15.22	20.73	12.62	14.05	15.20	19.59	15.06	14.47	14.10	17.48	15.03	13.88

Reforest	Mean	25.46	19.00	13.05	14.52	15.38	15.83	13.90	13.93	12.94	12.49	12.86	13.03
	SD	11.73	5.49	1.62	3.00	2.49	4.54	2.16	1.94	1.90	1.31	1.88	1.53
	STD error	2.62	1.14	0.34	0.62	0.52	0.95	0.45	0.40	0.40	0.27	0.39	0.32

Maize	Mean	32.65	28.24	14.98	15.69	16.94	17.00	15.63	14.72	14.24	14.32	14.32	13.91
	SD	15.58	7.53	1.17	2.41	3.75	2.41	2.35	1.26	1.29	2.06	2.90	1.32
	STD error	3.57	1.68	0.25	0.51	0.80	0.51	0.50	0.27	0.28	0.44	0.62	0.28

NH_4^+ (mg NH_4^+ -N kg^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	10.24	21.65	15.56	8.27	2.47	0.32	4.04	3.38	4.71	14.07	3.62	9.43
2	Reforestation	12.27	16.46	14.59	4.47	1.91	3.16	7.99	8.29	2.66	9.55	2.33	5.16
3	Reforestation	24.21	18.95	22.76	1.45	0.31	2.09	2.28	1.63	1.78	4.62	4.45	8.08
4	Reforestation	2.56	21.44	9.15	5.73	1.32	7.73	1.11	1.25	4.21	1.82	5.89	19.60
5	Reforestation	9.09	9.35	31.62	1.67	1.47	3.33	5.16	4.89	3.65	3.66	4.22	12.12
6	Maize	6.85	3.55	8.88	3.51	2.46	NA	1.18	0.62	10.40	2.98	30.02	19.72
7	Maize	7.04	10.06	11.65	1.39	4.61	NA	0.48	3.18	21.22	25.75	15.71	15.48
8	Maize	5.27	14.70	11.46	2.27	9.82	0.27	3.13	9.88	4.60	8.54	5.34	17.04
9	Maize	6.67	30.34	16.77	1.08	3.63	0.58	3.20	4.65	2.90	3.93	3.64	22.50
10	Maize	5.08	13.10	6.29	0.97	3.26	1.13	5.26	6.24	11.31	15.11	17.75	13.03
11	Reforestation	8.38	6.99	4.96	-0.37	1.94	1.96	0.26	2.29	2.87	3.77	13.93	14.85
12	Reforestation	7.62	24.59	19.05	0.95	7.11	8.66	3.92	9.08	10.54	19.98	31.15	12.65
13	Maize	3.13	4.94	6.57	5.72	6.82	0.59	5.98	17.91	5.74	6.39	7.66	28.55
14	Maize	14.59	15.59	3.80	1.41	2.43	5.47	7.04	3.05	6.82	16.35	4.59	13.10
15	Maize	5.00	12.53	16.83	3.01	1.33	NA	5.86	3.81	21.31	15.23	5.62	22.77
16	Reforestation	4.62	29.49	8.31	3.01	7.95	4.64	2.67	3.50	5.71	7.87	12.80	29.43
17	Reforestation	18.31	31.39	13.86	9.84	3.20	3.28	7.71	7.64	10.44	4.31	9.35	32.83
18	Reforestation	13.61	18.13	12.33	6.17	4.51	2.61	3.18	18.95	18.24	8.93	12.67	12.34
19	Reforestation	31.40	22.66	34.07	19.86	10.69	17.16	18.82	20.41	27.60	17.50	16.16	31.77
20	Reforestation	7.59	19.31	16.15	13.08	3.27	3.78	2.17	10.63	6.56	13.43	5.43	10.27
21	Maize	11.98	6.42	3.48	21.47	4.81	0.41	NA	7.16	29.97	6.10	35.16	32.75
22	Maize	23.81	14.14	13.86	0.13	2.29	1.01	5.99	10.82	8.95	2.95	23.60	22.45
23	Maize	10.83	9.65	12.33	1.76	0.73	32.04	36.80	9.96	2.48	2.64	26.64	10.08
24	Maize	30.27	3.33	34.07	7.01	2.55	6.10	27.88	25.44	4.90	2.57	28.75	13.58
25	Maize	31.16	18.91	16.15	3.84	2.32	6.22	10.79	33.50	13.07	24.06	26.92	18.49
26	Reforestation	17.39	22.05	3.48	22.29	4.88	2.01	9.93	18.86	11.39	11.01	18.92	18.77
27	Reforestation	11.51	17.16	8.47	9.03	4.59	6.64	8.73	10.34	18.72	12.96	7.51	17.21
28	Reforestation	14.78	20.59	7.04	8.61	6.49	13.79	6.86	23.12	22.14	19.20	30.06	22.79
29	Maize	2.71	10.88	5.80	0.99	5.71	1.61	2.71	2.79	12.22	6.45	7.10	25.79
30	Maize	3.90	0.49	4.44	4.30	7.65	4.82	2.48	4.03	23.97	4.65	22.45	29.74
31	Reforestation	2.34	1.71	7.41	5.84	1.45	2.79	6.94	28.24	45.91	2.97	21.19	18.76
32	Reforestation	6.49	21.98	6.96	4.18	6.93	2.87	18.68	17.08	26.42	3.20	13.23	15.58
33	Reforestation	2.02	15.48	37.00	5.35	3.37	8.28	23.50	4.25	21.51	10.55	9.51	10.25
34	Reforestation	2.61	21.53	15.95	2.70	18.73	2.82	8.14	3.43	23.02	1.91	17.86	4.11
35	Reforestation	3.24	23.90	16.29	9.95	3.99	2.52	2.41	5.23	10.10	12.78	7.69	8.26
36	Maize	19.16	8.20	6.49	1.77	12.20	1.83	3.07	1.04	17.31	1.46	4.94	11.39
37	Maize	14.35	7.84	7.73	3.14	8.55	14.13	4.94	3.15	15.21	2.73	8.91	10.22
38	Maize	14.14	11.02	12.27	11.78	12.02	2.78	0.95	1.57	10.16	3.11	3.98	24.22
39	Maize	24.76	9.26	13.05	5.25	26.92	10.82	2.90	2.77	12.39	2.81	26.61	23.50
40	Maize	6.74	20.10	5.04	0.73	13.85	8.09	4.71	2.80	27.68	1.36	22.85	12.26
41	Reforestation	4.53	14.75	7.85	5.76	5.03	3.36	4.42	22.21	4.62	3.59	18.95	6.86
42	Reforestation	7.75	15.99	19.55	18.60	17.70	7.33	27.14	9.57	2.67	2.08	4.58	26.84
43	Reforestation	3.19	16.51	23.98	3.42	3.79	2.28	6.68	3.26	11.88	4.44	1.48	21.16
44	Maize	20.71	25.34	7.47	3.65	4.37	2.59	7.57	7.28	8.85	5.63	4.64	31.92
45	Maize	7.62	6.98	10.84	1.03	8.42	0.79	2.37	10.01	15.41	5.82	8.02	18.79

Reforest	Mean	9.89	18.81	15.49	7.52	5.37	4.63	8.06	10.05	12.54	8.12	8.86	12.97
	SD	7.66	6.91	9.37	6.30	4.96	3.69	7.59	7.83	11.33	5.50	5.83	7.17
	STD error	1.67	1.78	2.42	1.63	1.28	0.95	1.96	2.02	2.93	1.42	1.51	1.85

Maize	Mean	12.98	12.02	10.89	3.83	6.66	5.59	9.39	12.66	45.91	25.75	35.16	32.83
	SD	8.80	7.21	6.81	4.83	6.03	7.66	9.92	10.42	1.78	1.36	1.48	3.64
	STD error	1.92	1.57	1.49	1.05	1.32	1.81	2.65	2.79	13.23	9.81	13.65	16.56

NO_3^- (mg NO_3^- -N kg^{-1})

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	10.24	21.65	15.56	8.27	2.47	0.32	4.04	3.38	4.71	14.07	3.62	9.43
2	Reforestation	12.27	16.46	14.59	4.47	1.91	3.16	7.99	8.29	2.66	9.55	2.33	5.16
3	Reforestation	24.21	18.95	22.76	1.45	0.31	2.09	2.28	1.63	1.78	4.62	4.45	8.08
4	Reforestation	2.56	21.44	9.15	5.73	1.32	7.73	1.11	1.25	4.21	1.82	5.89	19.60
5	Reforestation	9.09	9.35	31.62	1.67	1.47	3.33	5.16	4.89	3.65	3.66	4.22	12.12
6	Maize	6.85	3.55	8.88	3.51	2.46	NA	1.18	0.62	10.40	2.98	30.02	19.72
7	Maize	7.04	10.06	11.65	1.39	4.61	NA	0.48	3.18	21.22	25.75	15.71	15.48
8	Maize	5.27	14.70	11.46	2.27	9.82	0.27	3.13	9.88	4.60	8.54	5.34	17.04
9	Maize	6.67	30.34	16.77	1.08	3.63	0.58	3.20	4.65	2.90	3.93	3.64	22.50
10	Maize	5.08	13.10	6.29	0.97	3.26	1.13	5.26	6.24	11.31	15.11	17.75	13.03
11	Reforestation	8.38	6.99	4.96	-0.37	1.94	1.96	0.26	2.29	2.87	3.77	13.93	14.85
12	Reforestation	7.62	24.59	19.05	0.95	7.11	8.66	3.92	9.08	10.54	19.98	31.15	12.65
13	Maize	3.13	4.94	6.57	5.72	6.82	0.59	5.98	17.91	5.74	6.39	7.66	28.55
14	Maize	14.59	15.59	3.80	1.41	2.43	5.47	7.04	3.05	6.82	16.35	4.59	13.10
15	Maize	5.00	12.53	16.83	3.01	1.33	NA	5.86	3.81	21.31	15.23	5.62	22.77
16	Reforestation	4.62	29.49	8.31	3.01	7.95	4.64	2.67	3.50	5.71	7.87	12.80	29.43
17	Reforestation	18.31	31.39	13.86	9.84	3.20	3.28	7.71	7.64	10.44	4.31	9.35	32.83
18	Reforestation	13.61	18.13	12.33	6.17	4.51	2.61	3.18	18.95	18.24	8.93	12.67	12.34
19	Reforestation	31.40	22.66	34.07	19.86	10.69	17.16	18.82	20.41	27.60	17.50	16.16	31.77
20	Reforestation	7.59	19.31	16.15	13.08	3.27	3.78	2.17	10.63	6.56	13.43	5.43	10.27
21	Maize	11.98	6.42	3.48	21.47	4.81	0.41	NA	7.16	29.97	6.10	35.16	32.75
22	Maize	23.81	14.14	13.86	0.13	2.29	1.01	5.99	10.82	8.95	2.95	23.60	22.45
23	Maize	10.83	9.65	12.33	1.76	0.73	32.04	36.80	9.96	2.48	2.64	26.64	10.08
24	Maize	30.27	3.33	34.07	7.01	2.55	6.10	27.88	25.44	4.90	2.57	28.75	13.58
25	Maize	31.16	18.91	16.15	3.84	2.32	6.22	10.79	33.50	13.07	24.06	26.92	18.49
26	Reforestation	17.39	22.05	3.48	22.29	4.88	2.01	9.93	18.86	11.39	11.01	18.92	18.77
27	Reforestation	11.51	17.16	8.47	9.03	4.59	6.64	8.73	10.34	18.72	12.96	7.51	17.21
28	Reforestation	14.78	20.59	7.04	8.61	6.49	13.79	6.86	23.12	22.14	19.20	30.06	22.79
29	Maize	2.71	10.88	5.80	0.99	5.71	1.61	2.71	2.79	12.22	6.45	7.10	25.79
30	Maize	3.90	0.49	4.44	4.30	7.65	4.82	2.48	4.03	23.97	4.65	22.45	29.74
31	Reforestation	2.34	1.71	7.41	5.84	1.45	2.79	6.94	28.24	45.91	2.97	21.19	18.76
32	Reforestation	6.49	21.98	6.96	4.18	6.93	2.87	18.68	17.08	26.42	3.20	13.23	15.58
33	Reforestation	2.02	15.48	37.00	5.35	3.37	8.28	23.50	4.25	21.51	10.55	9.51	10.25
34	Reforestation	2.61	21.53	15.95	2.70	18.73	2.82	8.14	3.43	23.02	1.91	17.86	4.11
35	Reforestation	3.24	23.90	16.29	9.95	3.99	2.52	2.41	5.23	10.10	12.78	7.69	8.26
36	Maize	19.16	8.20	6.49	1.77	12.20	1.83	3.07	1.04	17.31	1.46	4.94	11.39
37	Maize	14.35	7.84	7.73	3.14	8.55	14.13	4.94	3.15	15.21	2.73	8.91	10.22
38	Maize	14.14	11.02	12.27	11.78	12.02	2.78	0.95	1.57	10.16	3.11	3.98	24.22
39	Maize	24.76	9.26	13.05	5.25	26.92	10.82	2.90	2.77	12.39	2.81	26.61	23.50
40	Maize	6.74	20.10	5.04	0.73	13.85	8.09	4.71	2.80	27.68	1.36	22.85	12.26
41	Reforestation	4.53	14.75	7.85	5.76	5.03	3.36	4.42	22.21	4.62	3.59	18.95	6.86
42	Reforestation	7.75	15.99	19.55	18.60	17.70	7.33	27.14	9.57	2.67	2.08	4.58	26.84
43	Reforestation	3.19	16.51	23.98	3.42	3.79	2.28	6.68	3.26	11.88	4.44	1.48	21.16
44	Maize	20.71	25.34	7.47	3.65	4.37	2.59	7.57	7.28	8.85	5.63	4.64	31.92
45	Maize	7.62	6.98	10.84	1.03	8.42	0.79	2.37	10.01	15.41	5.82	8.02	18.79

Reforest	Mean	9.89	18.81	15.49	7.52	5.37	4.63	8.06	10.05	12.54	8.12	8.86	12.97
	SD	7.66	6.91	9.37	6.30	4.96	3.69	7.59	7.83	11.33	5.50	5.83	7.17
	STD error	1.67	1.78	2.42	1.63	1.28	0.95	1.96	2.02	2.93	1.42	1.51	1.85

Maize	Mean	12.98	12.02	10.89	3.83	6.66	5.59	9.39	12.66	45.91	25.75	35.16	32.83
	SD	8.80	7.21	6.81	4.83	6.03	7.66	9.92	10.42	1.78	1.36	1.48	3.64
	STD error	1.92	1.57	1.49	1.05	1.32	1.81	2.65	2.79	13.23	9.81	13.65	16.56

Soil pH

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	6.13	5.75	6.16	6.01	5.98	6.05	5.62	5.74	6.05	6.33	6.05	6.37
2	Reforestation	6.07	5.68	5.64	5.80	5.70	5.71	5.81	5.88	5.94	5.93	6.02	6.25
3	Reforestation	5.86	5.94	5.99	5.93	5.95	5.96	5.95	5.68	5.96	6.06	5.88	5.94
4	Reforestation	5.68	5.76	6.16	5.87	5.93	5.98	5.98	6.34	6.05	6.39	5.89	5.80
5	Reforestation	5.93	6.08	5.93	5.98	6.00	5.97	5.61	6.17	6.07	6.31	5.79	6.23
6	Maize	6.21	6.19	5.35	5.91	5.82	5.69	5.95	6.19	6.17	6.59	5.99	6.12
7	Maize	6.04	6.22	5.69	5.99	5.97	5.88	5.87	6.27	6.11	6.00	6.06	5.96
8	Maize	6.11	5.96	6.35	6.14	6.15	6.22	6.00	6.19	6.37	6.32	6.19	6.00
9	Maize	6.10	5.89	6.29	6.09	6.09	6.16	6.07	6.29	6.38	6.04	6.30	6.02
10	Maize	6.13	6.05	6.40	6.19	6.21	6.27	6.07	6.32	6.32	6.15	6.11	6.15
11	Reforestation	6.09	6.16	6.28	6.18	6.21	6.22	6.01	6.00	6.40	6.33	6.25	6.23
12	Reforestation	6.07	5.98	6.20	6.08	6.09	6.12	5.87	6.05	6.23	6.17	6.02	6.15
13	Maize	6.10	6.21	6.33	6.22	6.25	6.27	5.98	6.20	6.40	6.31	6.26	6.06
14	Maize	5.99	5.87	6.35	6.07	6.10	6.17	5.94	6.21	6.43	6.17	6.23	6.08
15	Maize	6.16	6.08	6.14	6.13	6.12	6.13	5.99	6.21	5.21	6.25	6.22	6.18
16	Reforestation	6.23	6.14	6.25	6.21	6.20	6.22	6.13	6.27	6.39	6.59	6.58	6.07
17	Reforestation	6.09	6.22	6.37	6.23	6.27	6.29	6.13	6.13	6.16	6.51	6.43	6.15
18	Reforestation	6.01	6.21	6.30	6.17	6.23	6.23	6.14	5.93	6.08	6.36	6.27	6.33
19	Reforestation	5.98	5.90	6.14	6.01	6.01	6.05	5.91	5.91	6.03	6.20	6.23	6.17
20	Reforestation	5.85	5.84	6.09	5.92	5.95	5.99	6.18	5.92	6.12	6.12	6.28	6.29
21	Maize	6.00	6.25	6.27	6.17	6.23	6.22	6.25	6.20	5.74	6.46	6.27	5.74
22	Maize	5.87	6.21	6.09	6.06	6.12	6.09	6.20	6.21	6.25	6.60	6.37	5.98
23	Maize	5.90	6.17	6.19	6.09	6.15	6.14	5.77	5.85	6.47	6.53	6.30	6.13
24	Maize	5.72	6.12	6.07	5.97	6.05	6.03	5.95	5.83	6.39	6.56	6.34	6.22
25	Maize	5.74	6.09	6.10	5.98	6.06	6.04	5.89	5.83	6.25	6.38	6.24	6.31
26	Reforestation	5.96	6.09	6.23	6.09	6.14	6.16	5.91	6.10	6.11	6.37	6.37	6.29
27	Reforestation	5.85	6.15	6.08	6.03	6.08	6.06	5.96	6.02	6.01	6.46	6.37	5.95
28	Reforestation	5.86	6.12	6.11	6.03	6.09	6.08	5.91	5.62	5.95	6.18	5.70	6.10
29	Maize	6.14	6.13	6.29	6.19	6.20	6.23	5.75	6.11	5.92	6.16	6.12	5.40
30	Maize	6.07	6.18	6.25	6.17	6.20	6.21	5.94	6.12	5.81	6.32	6.07	5.57
31	Reforestation	6.26	6.28	6.41	6.32	6.34	6.35	6.05	6.04	5.78	6.47	6.37	6.01
32	Reforestation	6.10	6.23	6.24	6.19	6.22	6.22	6.11	6.10	6.08	6.09	6.60	6.21
33	Reforestation	6.02	6.28	6.22	6.17	6.22	6.21	5.87	6.12	6.13	6.55	6.65	6.32
34	Reforestation	6.17	6.26	6.31	6.25	6.27	6.28	6.14	6.38	6.09	6.60	6.64	6.52
35	Reforestation	6.13	6.28	6.24	6.22	6.25	6.23	6.20	6.37	6.26	6.63	6.59	6.41
36	Maize	6.09	6.50	6.47	6.35	6.44	6.42	6.34	6.42	6.03	6.79	6.69	6.43
37	Maize	6.19	6.31	6.44	6.32	6.36	6.37	6.28	6.46	6.25	6.82	6.56	6.47
38	Maize	6.06	6.29	6.44	6.26	6.33	6.34	6.39	6.45	6.38	6.68	6.70	6.32
39	Maize	6.09	6.36	6.44	6.30	6.36	6.37	6.46	6.51	6.60	6.82	6.66	6.26
40	Maize	6.20	6.29	6.51	6.33	6.38	6.41	6.48	6.58	6.46	6.87	6.32	6.16
41	Reforestation	6.15	6.31	6.20	6.22	6.24	6.22	5.96	6.22	6.58	6.85	6.62	6.29
42	Reforestation	6.01	6.18	6.18	6.12	6.16	6.16	5.81	6.44	6.65	6.92	6.79	5.86
43	Reforestation	6.29	6.13	6.31	6.24	6.23	6.26	6.11	6.47	6.57	6.97	6.70	5.95
44	Maize	5.99	6.05	6.32	6.12	6.16	6.20	5.74	6.53	6.55	6.81	6.69	5.84
45	Maize	6.01	6.14	6.16	6.10	6.13	6.13	5.96	6.35	6.29	6.63	6.61	6.08

Reforest	Mean	6.0350725	6.0850725	6.1756522	6.098599	6.1197746	6.1313419	5.9726087	6.0826087	6.1604348	6.4082609	6.3082609	6.1691304
	SD	0.1495781	0.1893846	0.1628268	0.1378764	0.1509733	0.1455522	0.163463	0.2343893	0.2216975	0.2731242	0.3173563	0.1847089
	STD error	0.0311892	0.0394894	0.0339517	0.0287492	0.0314801	0.0303497	0.0340844	0.0488735	0.0462271	0.0569503	0.0661734	0.0385145

Maize	Mean	6.0415152	6.1622727	6.224697	6.1428283	6.1765993	6.1813749	6.0577273	6.2422727	6.2172727	6.4663636	6.3318182	6.0672727
	SD	0.133776	0.1490903	0.2667672	0.1224835	0.1450178	0.1708081	0.2239671	0.2126686	0.3184214	0.2722839	0.223258	0.2572229
	STD error	0.0285211	0.0317862	0.0568749	0.0261136	0.0309179	0.0364164	0.0477499	0.0453411	0.0678877	0.0580511	0.0475988	0.0548401

WFPS (%)

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	0.42	0.74	0.80	0.68	0.79	0.45	0.38	0.38	0.43	0.14	0.21	0.29
2	Reforestation	0.56	0.71	0.87	0.72	0.88	0.72	0.62	0.76	0.70	0.54	0.42	0.47
3	Reforestation	0.42	0.78	0.79	0.86	0.87	0.60	0.34	0.68	0.68	0.41	0.34	0.34
4	Reforestation	0.50	0.76	0.73	0.82	0.88	0.48	0.43	0.41	0.43	0.33	0.31	0.18
5	Reforestation	0.46	0.72	0.77	0.72	0.67	0.51	0.41	0.38	0.42	0.27	0.34	0.21
6	Maize	0.24	0.47	0.34	0.50	0.53	0.25	0.07	0.12	0.04	0.13	0.03	0.02
7	Maize	0.28	0.39	0.51	0.45	0.56	0.31	0.14	0.14	0.08	0.02	0.05	0.04
8	Maize	0.40	0.50	0.60	0.69	0.54	0.37	0.21	0.33	0.22	0.15	0.25	0.11
9	Maize	0.34	0.28	0.66	0.64	0.70	0.35	0.15	0.20	0.19	0.06	0.22	0.14
10	Maize	0.35	0.26	0.87	0.77	0.63	0.36	0.18	0.26	0.19	0.08	0.22	0.20
11	Reforestation	0.22	0.71	0.60	0.31	0.43	0.33	0.20	0.15	0.19	0.09	0.11	0.07
12	Reforestation	0.34	0.83	0.72	0.45	0.78	0.42	0.22	0.15	0.23	0.11	0.14	0.09
13	Maize	0.36	0.39	0.55	0.58	0.71	0.42	0.28	0.18	0.35	0.22	0.22	0.14
14	Maize	0.67	0.59	0.86	0.57	0.81	0.51	0.27	0.25	0.27	0.16	0.24	0.18
15	Maize	0.53	0.60	0.70	0.54	0.81	0.39	0.47	0.19	0.31	0.25	0.24	0.22
16	Reforestation	0.49	0.61	0.78	0.87	0.83	0.54	0.43	0.54	0.49	0.23	0.29	0.33
17	Reforestation	0.56	0.50	0.74	0.86	0.73	0.59	0.44	0.30	0.51	0.13	0.12	0.13
18	Reforestation	0.57	0.54	0.82	0.79	0.83	0.58	0.50	0.39	0.40	0.20	0.14	0.10
19	Reforestation	0.58	0.67	0.75	0.81	0.85	0.51	0.48	0.33	0.41	0.14	0.17	0.16
20	Reforestation	0.37	0.50	0.66	0.76	0.82	0.62	0.46	0.38	0.52	0.33	0.29	0.31
21	Maize	0.26	0.50	0.77	0.54	0.78	0.34	0.23	0.07	0.17	0.16	0.31	0.16
22	Maize	0.26	0.38	0.80	0.53	0.68	0.36	0.18	0.31	0.16	0.26	0.35	0.06
23	Maize	0.21	0.43	0.60	0.59	0.70	0.26	0.13	0.07	0.18	0.27	0.08	0.08
24	Maize	0.29	0.40	0.78	0.84	0.82	0.18	0.11	0.03	0.20	0.16	0.08	0.05
25	Maize	0.34	0.60	0.78	0.73	0.84	0.24	0.13	0.07	0.21	0.16	0.07	0.02
26	Reforestation	0.50	0.56	0.73	0.78	0.85	0.46	0.27	0.34	0.31	0.18	0.18	0.14
27	Reforestation	0.51	0.68	0.88	0.82	0.82	0.67	0.49	0.47	0.47	0.23	0.20	0.29
28	Reforestation	0.43	0.75	0.87	0.65	0.76	0.63	0.37	0.44	0.46	0.17	0.15	0.23
29	Maize	0.45	0.24	0.66	0.49	0.66	0.48	0.26	0.15	0.26	0.14	0.11	0.06
30	Maize	0.33	0.42	0.74	0.73	0.66	0.42	0.33	0.23	0.31	0.17	0.12	0.01
31	Reforestation	0.48	0.67	0.64	0.81	0.81	0.69	0.51	0.48	0.62	0.17	0.43	0.36
32	Reforestation	0.67	0.65	0.65	0.76	0.87	0.49	0.44	0.30	0.65	0.35	0.39	0.47
33	Reforestation	0.65	0.73	0.68	0.84	0.94	0.64	0.37	0.27	0.49	0.20	0.36	0.26
34	Reforestation	0.74	0.68	0.63	0.69	0.91	0.61	0.33	0.27	0.52	0.22	0.19	0.32
35	Reforestation	0.78	0.73	0.87	0.73	0.89	0.51	0.47	0.27	0.48	0.15	0.32	0.31
36	Maize	0.46	0.45	0.54	0.63	0.89	0.57	0.36	0.21	0.44	0.22	0.16	0.18
37	Maize	0.41	0.46	0.67	0.56	0.85	0.58	0.38	0.19	0.37	0.26	0.21	0.23
38	Maize	0.34	0.41	0.74	0.77	0.86	0.35	0.44	0.20	0.54	0.19	0.15	0.21
39	Maize	0.37	0.45	0.72	0.51	0.72	0.44	0.49	0.23	0.50	0.18	0.12	0.14
40	Maize	0.46	0.51	0.60	0.56	0.68	0.38	0.34	0.27	0.31	0.15	0.11	0.12
41	Reforestation	0.29	0.54	0.75	0.79	0.83	0.55	0.33	0.35	0.49	0.22	0.23	0.25
42	Reforestation	0.47	0.56	0.59	0.73	0.89	0.78	0.73	0.39	0.71	0.30	0.26	0.22
43	Reforestation	0.61	0.48	0.67	0.58	0.90	0.39	0.25	0.36	0.65	0.26	0.19	0.34
44	Maize	0.64	0.62	0.58	0.58	0.89	0.56	0.45	0.17	0.46	0.17	0.12	0.20
45	Maize	0.38	0.56	0.79	0.61	0.90	0.47	0.41	0.19	0.26	0.15	0.22	0.15

Reforest	Mean	50.29	65.25	73.89	72.00	82.33	54.83	41.33	37.16	48.26	22.78	24.50	24.95
	SD	13.95	10.51	9.21	14.11	9.65	11.09	12.96	12.90	14.12	10.88	9.72	11.04
	STD error	2.08	1.38	1.18	1.89	1.26	1.42	1.70	1.63	1.78	1.49	1.22	1.41

Maize	Mean	38.16	45.07	67.26	60.73	73.94	38.17	26.12	18.29	26.42	16.70	15.77	12.48
	SD	12.68	10.71	13.36	10.81	11.50	10.74	12.93	8.04	12.56	6.82	9.01	7.39
	STD error	1.93	1.42	1.74	1.53	1.60	1.42	1.67	1.01	1.60	0.89	1.23	0.93

Soil temperature (ºC)

Sample	Land use	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
1	Reforestation	30.88	29.13	28.00	28.75	26.63	29.75	24.25	23.75	23.88	28.13	31.00	29.25
2	Reforestation	34.63	30.17	29.00	30.88	27.38	29.38	21.75	21.50	21.00	23.88	30.75	30.00
3	Reforestation	30.63	28.33	28.50	29.00	28.00	28.00	23.88	22.00	21.88	22.00	26.75	28.00
4	Reforestation	29.75	27.67	27.75	28.88	26.25	27.38	23.13	22.88	23.38	24.00	27.25	30.13
5	Reforestation	30.25	27.33	27.00	28.75	25.63	27.00	23.88	22.25	22.25	26.75	28.75	30.13
6	Maize	34.13	23.63	29.50	28.00	28.25	29.50	30.00	26.00	22.88	29.25	31.38	30.75
7	Maize	30.63	29.00	28.13	29.00	26.25	32.88	25.38	25.25	23.75	26.25	31.38	33.75
8	Maize	32.63	28.88	28.63	28.38	27.38	29.88	24.63	24.13	23.25	25.25	29.25	31.00
9	Maize	35.50	29.50	28.63	28.38	27.75	30.50	24.25	24.25	23.75	25.38	28.88	31.50
10	Maize	32.63	30.00	28.50	29.38	27.13	29.13	24.25	24.25	22.75	24.88	28.63	30.50
11	Reforestation	30.00	28.63	27.00	27.75	26.38	28.13	21.50	24.13	22.25	25.50	27.00	30.75
12	Reforestation	29.88	28.50	26.88	26.00	26.38	26.63	23.88	23.00	23.25	25.38	27.50	28.13
13	Maize	35.13	28.25	27.38	32.13	27.00	27.75	21.00	20.00	20.13	21.00	26.25	28.13
14	Maize	35.38	25.50	27.50	29.63	28.88	33.50	25.75	25.13	23.63	29.88	27.13	33.00
15	Maize	31.63	26.00	28.38	33.63	28.38	31.63	24.00	25.38	25.38	28.88	27.13	31.88
16	Reforestation	27.13	27.50	25.00	27.00	26.50	27.13	23.75	22.75	23.75	23.00	27.75	29.00
17	Reforestation	30.00	33.13	26.25	27.00	26.38	27.13	23.38	22.13	24.25	26.88	31.38	33.88
18	Reforestation	27.50	28.13	27.50	26.00	26.38	25.00	22.00	21.75	23.38	27.88	31.00	32.50
19	Reforestation	29.00	28.63	27.63	26.50	26.00	26.00	23.50	20.88	21.88	24.75	31.63	32.63
20	Reforestation	30.25	31.25	28.00	26.25	27.38	25.63	24.00	22.00	21.25	25.50	30.50	30.00
21	Maize	31.13	25.88	28.69	29.00	28.38	29.75	26.00	33.75	22.25	25.00	30.75	30.75
22	Maize	31.75	29.25	28.69	28.63	29.25	30.25	25.00	28.50	21.50	25.00	29.75	30.13
23	Maize	30.75	29.25	28.69	31.25	28.13	28.88	27.38	32.88	22.00	25.00	31.63	31.50
24	Maize	31.75	30.25	28.69	29.88	28.75	31.25	27.38	37.00	21.13	25.38	30.75	31.50
25	Maize	31.75	26.63	28.69	30.00	30.50	30.75	26.16	37.25	22.88	25.00	28.63	31.75
26	Reforestation	27.25	26.50	29.38	25.00	26.00	25.88	22.38	21.63	23.38	24.25	26.50	29.63
27	Reforestation	27.75	27.75	26.38	26.00	27.38	26.50	22.13	21.38	21.25	22.75	28.25	30.38
28	Reforestation	27.63	29.75	28.13	26.50	27.00	25.00	21.25	20.00	21.50	24.00	31.63	29.75
29	Maize	30.00	30.63	27.88	27.50	30.00	28.50	24.00	22.75	20.17	23.88	30.88	33.13
30	Maize	30.00	31.75	28.75	27.75	29.88	29.00	24.00	23.38	23.50	26.75	30.25	32.38
31	Reforestation	31.50	29.00	27.75	28.25	26.88	30.63	24.50	23.00	23.50	25.75	28.63	29.00
32	Reforestation	28.88	30.25	27.50	27.25	25.00	29.00	23.50	22.50	26.50	23.13	29.13	30.13
33	Reforestation	30.50	29.00	26.50	26.38	26.00	27.50	24.63	23.50	23.75	23.38	28.75	30.75
34	Reforestation	29.25	28.25	26.25	26.50	25.13	29.50	23.00	23.50	23.25	24.88	31.63	32.13
35	Reforestation	28.88	35.50	27.00	28.00	25.75	29.00	25.00	25.13	22.13	24.50	28.25	31.63
36	Maize	30.50	29.50	31.75	31.38	30.00	33.25	25.00	23.50	22.00	23.38	28.13	31.13
37	Maize	29.25	29.50	31.75	35.00	29.88	29.25	24.50	22.25	21.50	23.13	31.88	32.00
38	Maize	32.38	28.00	28.75	34.88	29.50	29.13	24.00	22.13	21.13	20.63	28.25	31.38
39	Maize	30.83	29.00	30.75	31.25	29.50	34.13	25.00	22.00	22.00	23.13	27.50	31.88
40	Maize	31.00	30.00	32.00	31.50	30.00	32.00	23.63	22.50	21.00	23.50	28.38	31.75
41	Reforestation	28.50	27.75	29.88	28.00	26.50	27.00	23.38	23.75	21.50	21.00	27.38	28.88
42	Reforestation	29.00	28.00	29.50	29.00	26.50	28.25	21.50	24.50	22.88	23.13	24.75	29.63
43	Reforestation	29.63	28.50	31.25	30.00	27.00	27.75	21.50	21.63	22.13	23.50	28.38	30.88
44	Maize	31.50	31.25	30.00	34.63	30.25	34.25	24.50	26.75	22.38	23.88	28.25	31.63
45	Maize	31.00	33.00	31.63	33.88	28.50	33.50	23.75	23.63	23.25	24.38	30.25	33.00

Reforest	Mean	29.59	29.07	27.55	27.48	26.40	27.64	23.28	22.76	22.88	24.59	26.41	29.42
	SD	1.68	2.08	1.22	1.42	0.74	1.50	1.04	1.12	1.28	1.86	2.63	1.61
	STD error	0.37	0.56	0.33	0.38	0.20	0.40	0.28	0.30	0.34	0.50	0.70	0.43

Maize	Mean	31.72	28.88	29.33	30.61	28.88	30.99	23.60	24.57	22.23	24.18	26.03	29.75
	SD	1.63	2.26	1.39	2.48	1.15	1.92	2.27	5.49	1.41	2.00	2.63	2.11
	STD error	0.36	0.49	0.30	0.54	0.25	0.42	0.63	1.52	0.39	0.56	0.73	0.59

Appendix 5: A comparison of N_2O emissions in riparian ecosystems to those of other ecosystems and by land use within each ecosystem.

The values without parentheses(*i.e.*, 999), values without parentheses and two values in parentheses (*i.e.*, 999(000-999)),and values separated by a dash without parentheses (*i.e.*, 000-999) are annual N_2O flux, annual and range N_2O flux, and range N_2O flux, respectively. The asterisk (*) indicates conventional drained water by farmer experience. Two asterisks (**) indicates units in kg N ha^{-2} 92 day^{-1}. The letters (nd) indicate not determinable.

Ecosystem and Land use types		**N_2O emission kg N ha^{-2} yr^{-1}**	**N input**		**Nitrogen content**		**Carbon content**		**Soil moisture**	**Reference**
			Type	**kg N ha^{-2} yr^{-1}**	**Type**	**mg N kg^{-1}**	**Type**	**g C kg^{-1}**		
1. Riparian and wetland tropical zone										
Riparian zone	Reforestation (Legume tree)	3.32 (0.31-12.60)	N fixation	54.55	NH_4^+ NO_3^-	4.89 10.78	Total C	17.75	4.62 -95.72% WFPS	This study
Riparian zone	Tropical forest, Puerto Rico		NA	NA					High level ground water	Bowden et al., 1992
	-Icacos watershed				Total N	3.6	Total C	81		
	- Topographic breaks	3.504 -26.28								
	- Hillslope	<= 0.175								
	- Bisley watershed	< 3.504			Total N	0.27	Total C	41		
Peat	Forested (drained and undrained peat swamp, agro-forestry), SEA	3.44 (-0.51-13.38)	NA	NA	NA	NA	NA	NA	60-90% WFPS	Couwenberg et al., 2010
Peat	Forest, Malaysia	0.7	NA	NA	NH_4^+ NO_3^-	54.9 78.8	Organic C	450-480	57.6% WFPS	Melling et al., 2007
Peat	Oil palm, Malaysia	1.2	NA	NA	NH_4^+ NO_3^-	58.2 198.4	Organic C	450-480	60 % WFPS	Melling et al., 2007
Riparian zone	Maize	2.24 (0.11-5.97)	N fertilizer and residual	197-294.92	NH_4^+ NO_3^-	3.91 10.29	Total C	14.89	0.61-98.23% WFPS	This study
Peat	Drained agricultural land (fertilized), SEA	90.96 (7.13-259.24)	NA	NA	NA	NA	NA	NA	60-90 % WFPS	Couwenberg et al., 2010
Peat	Drained, open vegetation (abandoned, not fertilized), SEA	0.70 (-1.08-4.01)	NA	NA	NA	NA	NA	NA	60-90 % WFPS	Couwenberg et al., 2010
Wetland	Paddy filed, Thailand	0.69	N Fertilizer	204.37	NH_4^+	19.6	Organic C	13.4	NA	Towprayoon et al., 2005
Peat	Paddy field, Indonesia	2.63-7.01	NA		NH_4^+ NO_3^-	83.5 1.7	Total C	123.7	NA	Hadi et al., 2000
Peat	Paddy field, SEA	0.64 (-0.38-2.04)	NA	NA	NA	NA	NA	NA	60-90% WFPS	Couwenberg et al., 2010

Ecosystem and Land use types		**N_2O emission kg N ha^{-2} yr^{-1}**	**N input**		**Nitrogen content**		**Carbon content**		**Soil moisture**	**Reference**
			Type	**kg N ha^{-2} yr^{-1}**	**Type**	**mg N kg^{-1}**	**Type**	**g C kg^{-1}**		
2. Riparian and wetland temperate zone										
Riparian zone	Mix vegetation , Belgium	-0.2 -0.9	NA	NA	Total N	25,100-45,500	Organic C	1.6-4.3	High level ground water	Dhondt et al., 2004
Riparian zone	Deciduous forest, Belgium	0.7 -2.1	NA	NA	Total N	22,000-33,900	Organic C	1.6-3.2	High level ground water	Boeckx and Van Cleemput, 2006
Riparian zone	Hard wood, Iowa, USA	1.8–4.0	N fertilizer, residual, leaching	1118.8-127.9	NH_4^+ NO_3^-	4.1 0.7	Total C	42.9	36.67% WFPS	Kim et al., 2009
Riparian zone	Forest, Mary land, USA	0.16-0.53	NA	NA	NO_3^-	<1	NA	NA	NA	Weller et al., 1994
Riparian zone	Hardwood, Mississippi, USA	0.04	NA	NA	NO_3^-	3.3	Soluble C	152	85% WFPS	Ullah et al., 2005
Riparian zone	Forest, Dutch	20	NO_3^- loading	467	NO_3^-	23-30	Organic C	46.5-162.8	60-80% WFPS	Hefting et al., 2003
Riparian zone	Grass, Dutch	2.4	NO3- loading	192	NO_3	4-9	Organic C	46.5-162.8	60-80% WFPS	Hefting et al., 2003
Riparian zone	Grass, Belgium	-0.2-2.0	NA	NA	Total N	32,000-57,700	Organic C	2.6-4.4	High level ground water	Boeckx and Van Cleemput, 2006
Riparian zone	Maize, Mary land, USA	2.7 (0.5-1.6)	NA	NA	NO_3^-	0.16-0.53	NA	NA	NA	Weller et al., 1994
Riparian zone	Maize and Soybean, Iowa, USA	7.2–16.8	N fertilizer and residual	99.9-223.2	NH_4^+ NO_3^-	1.7 1.2	Total C	22.8	55.67% WFPS	Kim et al., 2009
Riparian zone	Soybeans, Mississippi, USA	0.03	NA	NA	NO_3^-	3.5	Soluble C	137	85% WFPS	Ullah et al., 2005
Wetlands	Riparian wetlands constructed, Ohio, USA	0.70-1.92	NA	NA	NH_4^+ NO_3^-	0.97-14.33 0.75-9.75	Organic C	36.3-54.4	Situated soil	Hernandez et al., 2006
Wetland	Polar forest wetland, Hungary	0.044	NA	NA	Organic N	1,600	Organic C	2.19	Situated soil	Czóbel et al., 2010
Peat	Drained fen grassland, Slovenia	1.97	NA	NA	Organic N	880-1,400	Organic C	14-168	Situated soil	Danevcic et al., 2010
Peat	Cultivated grass, Norway	1.7	NA	NA	Total N	18,500-26,800	Organic C	288-488	Situated soil	Kløve et al., 2010

Ecosystem and Land use types		N_2O emission kg N ha^{-2} yr^{-1}	N input		Nitrogen content		Carbon content		Soil moisture	Reference
			Type	kg N ha^{-2} yr^{-1}	Type	mg N kg^{-1}	Type	g C kg^{-1}		
3. Terrestrial topical zone										
Forest	Dominant legume tree, Puerto Rico	0.48-0.77	NA	NA	NH_4^+ NO_3^-	7.5-15..0 14.7-34.0	Total C	50.7-72.5	30% WFPS	Erickson et al., 2002
Forest	Legume tree, Senegal	0.18-1.65	N fixation	NA	Inorganic N	2-16	Total C	7-12	NA	Dick et al., 2006
Forest	Primary forest, China	0.53	NA	NA	NA	NA	Organic C	19	25-70% WFPS	Werner et al., 2006
Forest	Secondary forest, China	0.64	NA	NA	NA	NA	Organic C	30	25-70% WFPS	Werner et al., 2006
Forest	Logged and primary forest, Indonesia,	9.31 (2.52-23.6)	NA	NA	NH4+ NO3-	1.94-14.61 1.16-8.07	Total C	25.7-213.9	22.6-70.3% WFPS	Ishizuka et al., 2005
Forest	>10 year Rubber Plantation, Indonesia	1.81 (0.14-4.91)	NA	NA	NH4+ NO3-	4.73-8.41 0.95-4.88	Total C	37.96 (22.9-64)	47.1-90.7% WFPS	Ishizuka et al., 2005
Forest	Rubber plantation, China	0.36	Fertilizer	55	NA	NA	Organic C	25	25-70% WFPS	Werner et al., 2006
Forest	Miombo woodland, Zimbabwe	0.9-1.9	NA	NA	NH_4^+ NO_3^-	3.84-7.66 1.32-7.58	Organic C	8.3-14.6	7.4-9.3% Soil moisture	Mapanda et al., 2010
Grass	Grassland, Zimbabwe	0.3-0.7	NA	NA	NH_4^+ NO_3^-	4.64-4.68 0.06-0.07	Organic C	10-20.9	9.9-15% Soil moisture	Mapanda et al., 2010
Crop	Peanut, Senegal	0.03-0.05	N fixation	37-206	Inorganic N	2-16	Total C	7-12	NA	Dick et al., 2006
Crop	Maize, upland , Chiang Mai, Northern, Thailand	0.59	Fertilizer	46.9	NA	NA	NA	NA	NA	Watanabe et al., 2000
Crop	Maize–groundnut crop rotation, Malaysia	0.77	Fertilizer N fixation	332 64.2	NA	NA	Organic C	12.5	30-80% WFPS	Khalil et al., 2002
Crop	Maize, Zimbabwe	0.5-1.6	Fertilizer	120	NH_4^+ NO_3^-	4.34-10.6 4.92-10.84	Organic C	5.9-23.1	6-7% Soil moisture	Mapanda et al., 2010
Crop	Maize, Indonesia	6.91**	Fertilizer	90	NH_4^+ NO_3^-	0.02 0.04	Organic C	19.7	NA	Hadi et al., 2008
4. Terrestrial temperate zone										
Forest	Mountain oak forest, Hungary	2.42	NA	NA	Organic N	2,200	Organic C	144	NA	Czóbel et al., 2010
Forest	European soil	4.97 (0.27-10.78)	N deposit	5-45	Total N	2,100-6,300	Organic C	2.1-6.3	20-80% WFPS	Schaufler et al., 2010
Grass	European soil	23.99 (3.80-45.27)	N deposit Fertilizer	13-20 16-230	Total N	4,100-8,500	Organic C	4.1-8.5	20-80% WFPS	Schaufler et al., 2010
Crop	European soil	2.51 (1.07-3.35)	N deposit Fertilizer	13-47 31-545	Total N	1,600-2,200	Organic C	1.6-2.2	20-80% WFPS	Schaufler et al., 2010
Crop	Maize, Northeast, China	0.47-4.51	Fertilizer	345	Total N	760	Organic C	9.40	NA	Chen et al., 2000
Crop	Grain legume crop, semiarid region, Australia	0.13	N fixation	67	Total N	0.00007	Total C	0.00938	<2-43 % WFPS	Barton et al., 2011

Appendix 6 Comparison of N_2O, WFPS, NO_3^- and soil temperature soil properties in maize area between simulated by DNDC and field experiment

N_2O simulated value (kg N ha^{-1})

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	0.242	0.117	0.090	0.092	0.269	0.027	0.019	0.010	0.017	0.010	0.011	0.034
7	0.325	0.133	0.112	0.124	0.376	0.032	0.022	0.016	0.026	0.010	0.012	0.036
8	0.229	0.152	0.161	0.142	0.392	0.038	0.027	0.020	0.030	0.030	0.031	0.045
9	0.041	0.038	0.058	0.036	0.040	0.021	0.014	0.010	0.010	0.010	0.015	0.057
10	0.045	0.040	0.068	0.042	0.049	0.023	0.017	0.010	0.013	0.010	0.015	0.079
13	0.059	0.056	0.139	0.059	0.068	0.032	0.022	0.020	0.016	0.010	0.015	0.083
14	0.051	0.048	0.102	0.047	0.054	0.028	0.020	0.015	0.016	0.010	0.012	0.056
15	0.052	0.048	0.099	0.051	0.059	0.028	0.020	0.016	0.020	0.010	0.019	0.087
21	0.420	0.194	0.268	0.205	0.671	0.042	0.027	0.020	0.260	0.020	0.022	0.042
22	0.401	0.205	0.285	0.223	0.713	0.046	0.032	0.022	0.306	0.020	0.024	0.051
23	0.375	0.195	0.278	0.217	0.707	0.045	0.031	0.021	0.312	0.020	0.025	0.053
24	0.402	0.201	0.282	0.223	0.727	0.049	0.032	0.023	0.303	0.020	0.025	0.051
25	0.405	0.221	0.310	0.245	0.791	0.051	0.034	0.030	0.368	0.020	0.026	0.061
29	0.036	0.041	0.169	0.036	0.040	0.022	0.019	0.010	0.044	0.010	0.012	0.046
30	0.045	0.047	0.194	0.044	0.047	0.026	0.020	0.017	0.058	0.010	0.014	0.057
36	0.057	0.056	0.241	0.054	0.059	0.031	0.022	0.020	0.019	0.010	0.016	0.080
37	0.051	0.061	0.240	0.049	0.057	0.031	0.022	0.020	0.017	0.010	0.015	0.064
38	0.049	0.060	0.230	0.048	0.055	0.030	0.021	0.020	0.017	0.010	0.015	0.061
39	0.054	0.063	0.242	0.049	0.056	0.031	0.022	0.020	0.016	0.010	0.015	0.062
40	0.052	0.059	0.251	0.050	0.057	0.031	0.022	0.019	0.016	0.010	0.015	0.063
44	0.057	0.066	0.256	0.055	0.062	0.032	0.023	0.020	0.020	0.020	0.022	0.069
45	0.048	0.059	0.229	0.048	0.056	0.031	0.021	0.020	0.018	0.010	0.015	0.064

N_2O observed value (kg N ha^{-1})

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	0.187	0.226	0.111	0.075	0.171	0.101	0.069	0.144	0.321	0.152	0.104	0.000
7	0.356	0.308	0.162	0.157	0.217	0.242	0.048	0.191	0.199	0.087	0.080	0.158
8	0.114	0.108	0.138	0.317	0.230	0.185	0.126	0.437	0.165	0.176	0.027	0.132
9	0.070	0.082	0.212	0.176	0.464	0.058	0.070	0.361	0.370	0.320	0.000	0.283
10	0.184	0.009	0.183	0.505	0.449	0.133	0.077	0.153	0.090	0.000	0.148	0.338
13	0.137	0.183	0.105	0.166	0.156	0.238	0.154	0.496	0.119	0.378	0.130	0.326
14	0.014	0.198	0.337	0.220	0.340	0.115	0.082	0.389	0.239	0.150	0.073	0.204
15	0.131	0.190	0.326	0.151	0.190	0.307	0.178	0.106	0.284	0.090	0.301	0.187
21	0.191	0.182	0.205	0.154	0.183	0.079	0.070	0.112	0.000	0.181	0.100	0.042
22	0.372	0.142	0.227	0.131	0.184	0.090	0.096	0.109	0.222	0.132	0.205	0.051
23	0.152	0.116	0.145	0.157	0.195	0.344	0.064	0.103	0.158	0.092	0.132	0.000
24	0.177	0.139	0.118	0.373	0.146	0.154	0.095	0.160	0.134	0.068	0.101	0.124
25	0.092	0.156	0.301	0.000	0.301	0.160	0.139	0.067	0.184	0.111	0.039	0.108
29	0.341	0.178	0.000	0.188	0.382	0.301	0.174	0.066	0.123	0.000	0.178	0.164
30	0.083	0.168	0.174	0.298	0.419	0.211	0.073	0.199	0.139	0.102	0.078	0.045
36	0.388	0.280	0.300	0.160	0.000	0.233	0.078	0.110	0.452	0.081	0.000	0.069
37	0.316	0.308	0.486	0.304	0.000	0.278	0.019	0.181	0.282	0.272	0.088	0.103
38	0.343	0.419	0.120	0.419	0.000	0.338	0.118	0.097	0.174	0.113	0.139	0.081
39	0.100	0.173	0.218	0.337	0.277	0.470	0.140	0.157	0.476	0.328	0.107	0.080
40	0.217	0.223	0.187	0.170	0.308	0.241	0.080	0.036	0.315	0.106	0.084	0.017
44	0.178	0.208	0.198	0.202	0.025	0.193	0.141	0.101	0.000	0.084	0.183	0.033
45	0.151	0.181	0.144	0.417	0.000	0.391	0.103	0.148	0.098	0.162	0.203	0.240

WFPS simulated value (0-1)

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	0.30	0.40	0.41	0.42	0.41	0.25	0.25	0.24	0.34	0.24	0.24	0.35
7	0.31	0.41	0.42	0.43	0.42	0.26	0.26	0.24	0.35	0.25	0.24	0.36
8	0.30	0.40	0.41	0.42	0.41	0.25	0.25	0.24	0.34	0.24	0.24	0.35
9	0.24	0.33	0.33	0.37	0.39	0.22	0.22	0.21	0.27	0.21	0.20	0.28
10	0.24	0.33	0.33	0.37	0.39	0.23	0.23	0.22	0.27	0.22	0.21	0.28
13	0.23	0.33	0.33	0.36	0.39	0.21	0.21	0.21	0.23	0.20	0.19	0.27
14	0.29	0.34	0.35	0.37	0.38	0.25	0.25	0.23	0.28	0.20	0.20	0.32
15	0.24	0.33	0.33	0.37	0.39	0.22	0.22	0.21	0.27	0.21	0.20	0.28
21	0.36	0.43	0.42	0.45	0.45	0.30	0.30	0.26	0.39	0.27	0.27	0.41
22	0.36	0.44	0.42	0.45	0.45	0.30	0.30	0.26	0.40	0.28	0.28	0.41
23	0.36	0.44	0.42	0.45	0.45	0.30	0.30	0.27	0.40	0.29	0.29	0.41
24	0.36	0.43	0.42	0.45	0.45	0.30	0.30	0.26	0.39	0.28	0.28	0.41
25	0.36	0.44	0.42	0.45	0.45	0.30	0.30	0.26	0.40	0.28	0.28	0.41
29	0.28	0.35	0.33	0.36	0.36	0.25	0.25	0.23	0.29	0.20	0.20	0.32
30	0.28	0.35	0.33	0.36	0.36	0.25	0.25	0.23	0.28	0.20	0.20	0.32
36	0.24	0.36	0.34	0.35	0.39	0.22	0.22	0.21	0.25	0.20	0.20	0.29
37	0.29	0.36	0.36	0.37	0.39	0.25	0.25	0.23	0.28	0.20	0.20	0.33
38	0.29	0.36	0.36	0.37	0.39	0.26	0.25	0.23	0.28	0.20	0.20	0.33
39	0.29	0.36	0.36	0.37	0.39	0.25	0.25	0.23	0.27	0.20	0.20	0.33
40	0.29	0.36	0.36	0.37	0.39	0.25	0.25	0.23	0.27	0.20	0.20	0.33
44	0.29	0.36	0.36	0.37	0.39	0.25	0.25	0.23	0.27	0.20	0.20	0.33
45	0.29	0.36	0.36	0.37	0.39	0.26	0.26	0.23	0.28	0.20	0.20	0.33

WFPS observed value (0-1)

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	0.24	0.47	0.34	0.50	0.53	0.25	0.07	0.12	0.04	0.13	0.03	0.02
7	0.28	0.39	0.51	0.45	0.56	0.31	0.14	0.14	0.08	0.02	0.05	0.04
8	0.40	0.50	0.60	0.69	0.54	0.37	0.21	0.33	0.22	0.15	0.25	0.11
9	0.34	0.28	0.66	0.64	0.70	0.35	0.15	0.20	0.19	0.06	0.22	0.14
10	0.35	0.26	0.87	0.77	0.63	0.36	0.18	0.26	0.19	0.08	0.22	0.20
13	0.36	0.39	0.55	0.58	0.71	0.42	0.28	0.18	0.35	0.22	0.22	0.14
14	0.67	0.59	0.86	0.57	0.81	0.51	0.27	0.25	0.27	0.16	0.24	0.18
15	0.53	0.60	0.70	0.54	0.81	0.39	0.47	0.19	0.31	0.25	0.24	0.22
21	0.26	0.50	0.77	0.54	0.78	0.34	0.23	0.07	0.17	0.16	0.31	0.16
22	0.26	0.38	0.80	0.53	0.68	0.36	0.18	0.31	0.16	0.26	0.35	0.06
23	0.21	0.43	0.60	0.59	0.70	0.26	0.13	0.07	0.18	0.27	0.08	0.08
24	0.29	0.40	0.78	0.84	0.82	0.18	0.11	0.03	0.20	0.16	0.08	0.05
25	0.34	0.60	0.78	0.73	0.84	0.24	0.13	0.07	0.21	0.16	0.07	0.05
29	0.45	0.24	0.66	0.49	0.66	0.48	0.26	0.15	0.26	0.14	0.11	0.06
30	0.33	0.42	0.74	0.73	0.66	0.42	0.33	0.23	0.31	0.17	0.12	0.01
36	0.46	0.45	0.54	0.63	0.89	0.57	0.36	0.21	0.44	0.22	0.16	0.18
37	0.41	0.46	0.67	0.56	0.85	0.58	0.38	0.19	0.37	0.26	0.21	0.23
38	0.34	0.41	0.74	0.77	0.86	0.35	0.44	0.20	0.54	0.19	0.15	0.21
39	0.37	0.45	0.72	0.51	0.72	0.44	0.49	0.23	0.50	0.18	0.12	0.14
40	0.46	0.51	0.60	0.56	0.68	0.38	0.34	0.27	0.31	0.15	0.11	0.12
44	0.64	0.62	0.58	0.58	0.89	0.56	0.45	0.17	0.46	0.17	0.12	0.20
45	0.38	0.56	0.79	0.61	0.90	0.47	0.41	0.19	0.26	0.15	0.22	0.15

NO$_3^-$ simulated value (kg N ha^{-1})

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	0.00	0.00	0.10	0.00	NA	0.00	0.00	0.04	0.07	0.10	0.14	31.40
7	0.00	0.00	0.10	0.00	NA	0.00	0.00	0.04	0.08	0.12	0.18	31.40
8	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.04	0.11	0.23	0.32	31.40
9	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.04	0.06	0.10	0.13	31.40
10	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.04	0.06	0.11	0.13	31.40
13	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.12	31.40
14	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.12	31.40
15	0.00	0.00	0.10	0.00	NA	0.00	0.00	0.04	0.05	0.08	0.12	31.40
21	27.57	0.00	0.12	0.80	0.00	NA	0.00	0.04	0.05	0.06	0.13	31.90
22	47.01	0.00	0.18	0.86	0.00	0.00	0.00	0.04	0.05	0.07	0.13	31.90
23	25.01	0.00	0.12	0.86	0.00	0.00	0.00	0.04	0.05	0.08	0.14	31.90
24	53.33	0.25	0.17	0.88	0.00	0.00	0.00	0.04	0.05	0.07	0.13	31.90
25	63.80	3.64	0.17	8.72	0.00	0.00	0.00	0.04	0.05	0.08	0.14	31.90
29	4.94	0.00	0.11	0.97	0.00	0.00	0.00	0.04	0.04	0.04	0.12	31.90
30	8.69	0.00	0.11	1.11	0.00	0.00	0.00	0.04	0.04	0.04	0.12	31.90
36	29.06	0.00	0.10	0.18	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30
37	25.77	0.00	0.10	0.22	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30
38	28.51	0.00	0.10	0.20	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30
39	38.66	0.00	0.10	0.22	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30
40	16.79	0.00	0.10	0.23	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30
44	39.90	0.00	0.11	0.26	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30
45	15.88	0.00	0.10	0.24	0.00	0.00	0.00	0.04	0.04	0.04	0.12	32.30

NO$_3^-$ observed value (kg N ha^{-1})

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	11.77	4.52	13.27	5.53	4.04	NA	1.72	0.89	14.93	4.72	45.91	29.46
7	12.00	12.84	17.75	1.93	7.33	NA	0.74	5.13	31.33	41.61	25.23	24.45
8	8.32	19.07	17.49	3.57	14.14	0.42	4.81	16.25	6.30	12.41	8.51	25.55
9	11.13	40.39	26.90	1.69	6.17	0.92	5.03	6.86	4.15	5.62	6.12	34.21
10	7.06	17.50	9.96	1.53	4.93	1.82	6.61	8.48	15.35	21.53	27.54	20.73
13	5.23	5.58	9.01	8.50	9.93	0.88	9.77	22.07	9.35	9.73	12.34	46.22
14	25.85	20.47	6.05	2.17	3.87	8.88	9.88	4.42	10.33	27.75	7.26	22.00
15	7.30	16.63	24.52	4.15	2.19	NA	9.89	4.39	32.31	24.65	9.00	36.32
21	16.80	9.35	5.69	32.11	8.19	0.69	NA	10.51	38.77	9.63	47.75	48.66
22	33.03	18.28	21.95	0.19	3.76	1.59	9.29	17.33	10.14	4.77	34.45	32.87
23	15.35	13.32	17.74	2.80	1.19	47.69	49.44	12.02	3.50	4.40	39.66	15.28
24	43.85	4.62	52.44	12.31	4.39	9.30	38.10	36.85	7.02	4.01	43.25	20.42
25	44.45	26.52	23.74	5.92	3.96	10.02	16.41	49.63	18.80	35.13	36.98	24.82
29	4.18	13.72	8.90	1.55	9.09	2.74	4.18	4.02	17.54	10.52	10.21	37.88
30	5.39	0.68	7.05	6.53	11.30	7.36	3.63	5.99	36.30	7.12	34.74	41.22
36	29.02	11.66	9.42	2.68	19.02	3.02	4.42	1.53	24.23	2.22	6.56	15.33
37	20.48	10.21	11.29	4.45	13.07	22.29	7.44	4.37	20.59	4.17	11.27	15.79
38	19.75	14.07	19.62	19.53	17.85	4.14	1.66	2.32	16.31	4.91	6.16	36.67
39	35.34	12.33	18.95	7.67	38.87	16.86	4.88	3.78	19.13	4.83	39.06	33.70
40	10.72	27.43	7.36	1.07	19.14	12.03	7.14	4.34	35.51	2.20	34.60	17.60
44	29.56	32.74	9.57	4.59	6.29	3.94	11.58	9.88	11.92	8.50	6.06	50.32
45	11.05	8.59	14.79	1.44	12.68	1.21	3.67	12.72	18.32	8.94	12.07	28.26

Soil temperature simulated value (ºC)

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
7	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
8	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
9	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
10	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
13	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
14	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
15	30.50	27.30	27.40	28.40	27.60	28.50	23.30	23.60	22.90	26.10	29.00	31.40
21	30.30	28.00	27.40	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
22	30.30	28.00	27.40	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
23	30.30	28.00	27.40	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
24	30.30	28.00	27.50	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
25	30.30	28.00	27.40	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
29	30.30	28.00	27.50	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
30	30.30	28.00	27.50	26.30	29.40	27.40	23.30	24.00	23.60	27.00	28.70	31.90
36	30.10	27.40	28.20	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30
37	30.10	27.40	28.30	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30
38	30.10	27.40	28.30	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30
39	30.10	27.40	28.30	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30
40	30.10	27.40	28.20	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30
44	30.10	27.40	28.30	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30
45	30.10	27.40	28.30	28.20	27.00	29.60	24.90	23.80	23.90	25.80	28.80	32.30

Soil temperature observed value (ºC)

Sample	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10
6	34.13	23.63	29.50	28.00	28.25	29.50	30.00	26.00	22.88	29.25	31.38	30.75
7	30.63	29.00	28.13	29.00	26.25	32.88	25.38	25.25	23.75	26.25	31.38	33.75
8	32.63	28.88	28.63	28.38	27.38	29.88	24.63	24.13	23.25	25.25	29.25	31.00
9	35.50	29.50	28.63	28.38	27.75	30.50	24.25	24.25	23.75	25.38	28.88	31.50
10	32.63	30.00	28.50	29.38	27.13	29.13	24.25	24.25	22.75	24.88	28.63	30.50
13	35.13	28.25	27.38	32.13	27.00	27.75	21.00	20.00	20.13	21.00	26.25	28.13
14	35.38	25.50	27.50	29.63	28.88	33.50	25.75	25.13	23.63	29.88	27.13	33.00
15	31.63	26.00	28.38	33.63	28.38	31.63	24.00	25.38	25.38	28.88	27.13	31.88
21	31.13	25.88	28.69	29.00	28.38	29.75	26.00	33.75	22.25	25.00	30.75	30.75
22	31.75	29.25	28.69	28.63	29.25	30.25	25.00	28.50	21.50	25.00	29.75	30.13
23	30.75	29.25	28.69	31.25	28.13	28.88	27.38	32.88	22.00	25.00	31.63	31.50
24	31.75	30.25	28.69	29.88	28.75	31.25	27.38	37.00	21.13	25.38	30.75	31.50
25	31.75	26.63	28.69	30.00	30.50	30.75	26.16	37.25	22.88	25.00	28.63	31.75
29	30.00	30.63	27.88	27.50	30.00	28.50	24.00	22.75	20.17	23.88	30.88	33.13
30	30.00	31.75	28.75	27.75	29.88	29.00	24.00	23.38	23.50	26.75	30.25	32.38
36	30.50	29.50	31.75	31.38	30.00	33.25	25.00	23.50	22.00	23.38	28.13	31.13
37	29.25	29.50	31.75	35.00	29.88	29.25	24.50	22.25	21.50	23.13	31.88	32.00
38	32.38	28.00	28.75	34.88	29.50	29.13	24.00	22.13	21.13	20.63	28.25	31.38
39	30.83	29.00	30.75	31.25	29.50	34.13	25.00	22.00	22.00	23.13	27.50	31.88
40	31.00	30.00	32.00	31.50	30.00	32.00	23.63	22.50	21.00	23.50	28.38	31.75
44	31.50	31.25	30.00	34.63	30.25	34.25	24.50	26.75	22.38	23.88	28.25	31.63
45	31.00	33.00	31.63	33.88	28.50	33.50	23.75	23.63	23.25	24.38	30.25	33.00

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