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**Tillage-Induced Soil Nitrous Oxide Fluxes
from Two Soils in the Manawatu**

A THESIS PRESENTED IN PARTIAL FULFILMENT OF
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Abstract

Enhanced greenhouse gas emissions of nitrous oxide (N_2O) induced by agricultural practices is believed to be the major anthropogenic source. Studies conducted in New Zealand generally from pasture suggest low N_2O emission, however, there is little information for arable farming systems. Therefore, there is a need for a site-specific assessment of the impact of tillage practices on N_2O fluxes.

This paper evaluates tillage system and land use effects on N_2O emissions at two sites using a closed chamber technique. Sites included a Kairanga silt loam where maize/barley was grown continuously for either 17 (K17) or 34 (K34) years, with a conventional tillage system (Kairanga), and an Ohakea silt loam where winter oats and summer fodder maize was double-cropped for five years with conventional (CT) and no-tillage (NT) systems (Massey). At both sites permanent pasture (PP) soil was used as a control.

Spatial measurements for all treatments at Massey site showed large inherent variations in N_2O fluxes (a mean $\text{CV}=119\%$) which reflected natural soil heterogeneity, and perhaps the measurement technique used rather than the real differences due to the tillage and cropping systems evaluated. N_2O emissions measured from December 1998 to September 1999 from the PP were significantly lower ($1.66 \text{ kg } \text{N}_2\text{O-N/ha/year}$) than the CT and NT plots at 9.20 and $12.00 \text{ kg } \text{N}_2\text{O-N/ha/year}$ respectively. However, there were no differences in N_2O emission rates between the CT and NT treatments. Cumulative coefficient of variation (CV) of treatments ranged from 39 to 140%.

Seedbed preparation using power-harrow which was done within few days of ploughing the CT plots reduced N_2O emissions by 65% within the first hour after power-harrowing. However, N_2O emission rates returned to the pre-power harrowing levels one month after power-harrowing.

There was strong relationship between log-transformed values of soil moisture content (SMC) and N_2O emissions in all treatments, PP ($r = 0.73$), CT ($r = 0.75$) and NT ($r = 0.86$). Seasonal variation in N_2O emission from the PP was in the order of winter=autumn>summer. Although fluxes in the CT were higher in winter than in the autumn season, there were no differences between the summer and autumn data. Similar

to the PP, the seasonal variations in N_2O emission in the NT treatment were in the order of winter>autumn=summer.

The estimated annual N_2O emissions from the PP, K17 and K34 (calculated as the mean of all individual closed cover chamber measurements between November 1998 and September 1999) from Kairanga site were similar at 3.24, 3.42 and 2.37 kg N_2O -N/ha/year, respectively. There were large variations in N_2O emissions during the year with the mean flux rates ranging from 0.175 to 13.32, 0.175 to 16.91 and 0.088 to 30.05 kg N_2O -N/ha/year in the PP, K17 and K34 fields, respectively.

Although overall comparison of treatment means did not show any discernible differences between management practices, there were signs that the K34 had lower emissions compared to the PP.

N_2O fluxes from the K17 and PP field appeared to be influenced by SMC. There is clear indication that low or negligible emissions occur when gravimetric soil water content is less than 30% in the PP. Although N_2O fluxes did not follow the rainfall patterns in the K17 and PP, linear regression analyses indicated low but significant relationship $r = 0.46$ and 0.53 (0.72 when log-transformed), respectively.

In the K34 field, SMC did not seem to govern fluxes which were especially apparent during wet months of April and May. The linear regression analysis using the measured data revealed no relationship ($r = 0.12$) between the SMC and N_2O fluxes in the K34 treatment.

Seasonal grouping of monthly log-transformed N_2O emissions showed significant differences in all treatments. Summer season N_2O emissions in the PP were the lowest than other seasons whereas no discernible differences were observed among other seasons. Although N_2O fluxes during spring and summer were similar in the K17 field, they were significantly lower than the winter and higher than autumn fluxes. There were considerably higher emissions in summer than in autumn in the K34 but seasonal variation between winter and spring was less profound.

Spatial variability in N_2O fluxes was large during the year with coefficients of variation (CV) ranging from 10 to 82%, 12 to 99% and 9 to 137% for the PP, K17 and K34 fields, respectively.

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Table of Contents

Abstract	i
Acknowledgements	iii
Table of Contents	iv
List of Tables	viii
List of Figures	x
 Chapter 1 - General Introduction	 1
1.1 Research Objectives	3
 Chapter 2 - Literature Review	 4
2.1 Introduction	4
2.2 Nitrous Oxide in the Atmosphere	6
2.3 Sources of Nitrous Oxide	6
2.4 Impact of Nitrous Oxide on the Environment	7
2.5 Global Nitrogen Perspective	8
2.6 Status of Nitrous Oxide Emissions in New Zealand	10
2.7 The Role of Micro-Organisms	12
2.8 Mechanisms of Nitrous Oxide Production	12
2.8.1 Denitrification	12
2.8.2 Nitrification	13
2.8.3 Sinks	14
2.9 Agriculture as a Major Source of Nitrous Oxide Emissions	16
2.9.1 Effects of Tillage Practices	16

2.9.2 The Role of Fertilisers	17
2.10 Factors Controlling Nitrous Oxide Emission	18
2.10.1 Soil Properties	18
2.10.2 Soil Organic Matter	20
2.10.3 Soil Moisture Content	21
2.10.4 Soil pH	22
2.10.5 Temperature	22
2.11 Soil Management Practices Impacting Nitrous Oxide Emission	23
2.12 Field Nitrous Oxide Emission Measurement Methods	24
2.12.1 Chamber Methods	25
2.12.2 Micrometeorological Methods	27
2.12.3 Ultra-Large Chambers with Long-Path IR Spectrometers	28
2.12.4 Nitrous Oxide Emissions Variability	29
2.13 Summary	30
Chapter 3 - Materials and Methods	31
3.1 Experimental Sites	31
3.1.1 Kairanga Site	32
3.1.2 Massey Site	34
3.2 Measurement of Field N₂O Emission	37
3.2.1 Procedure	38
3.2.2 Analysis of N ₂ O Concentration	42
3.3 Pilot Experiments	42
3.3.1 Exploratory Sampling	42
3.3.2 Spatial Variability	43
3.3.3 N ₂ O Emissions During Seedbed Preparation	43

3.3.4 Prolonged Continuous Measurement	43
3.4 Ancillary Measurements	43
3.4.1 Soil Moisture	43
3.4.2 Soil Temperature	43
3.4.3 Soil pH, Total C and N	44
3.4.4 Rainfall Data	44
3.4.5 Statistical Analysis	44
Chapter 4 - Results and Discussion	46
4.1 Overview	46
4.2 Pilot Experiment	47
4.2.1 Exploratory Sampling	47
4.2.2 Spatial Variation	48
4.2.3 Pilot Experiment on Effect of Seedbed Preparation on N ₂ O Emission	48
4.2.4 Effect of Prolonged Measurements on N ₂ O Flux	50
4.3 Massey Experimental Site	50
4.3.1 Effects of Tillage on Soil pH, Total C and N	50
4.3.1.1 <i>Effect of Tillage Techniques on Soil pH</i>	52
4.3.1.2 <i>Effect of Tillage Techniques on Total C</i>	52
4.3.1.3 <i>Effect of Tillage Technique on Total N</i>	53
4.3.2 Tillage Effect on Field N ₂ O Emissions	53
4.3.3 Summary	59
4.3.3.1 <i>Effect of Soil Moisture on N₂O Emissions</i>	59
4.3.3.2 <i>Seasonal Variation</i>	62
4.3.3.3 <i>Spatial Variation</i>	65
4.3.4 Summary	67

4.4 Kairanga Experimental Site	68
4.4.1 Effects of Tillage on Soil pH, Total C and N	68
4.4.2 Tillage Effect on Field N₂O Emissions	68
<i>4.4.2.1 Effect of Soil Moisture on N₂O Emissions</i>	74
<i>4.4.2.2 Seasonal Variation</i>	79
<i>4.4.2.3 Spatial Variation</i>	82
4.4.3 Summary	83
Chapter 5 - Conclusions	84
5.1 General	84
5.2 Massey Experimental Site (<i>Ohakea Silt Loam Soil</i>)	84
5.3 Kairanga Experimental Site (<i>Kairanga Silt Loam Soil</i>)	86
References	88
Appendices	

List Of Tables

Table 2.1:	Atmospheric concentrations of the major greenhouse gases, their rise, residence time and contribution to the global warming.	6
Table 2.2:	Biogeochemical distribution of N on Earth.	9
Table 2.3:	Global fluxes of nitrogen into and out of the terrestrial biosphere.	9
Table 2.4:	Comparison of flux measurements by flux gradient micro-meteorological, combined megachamber/long-path IR, and small chamber gas chromatograph (GC) methods.	26
Table 3.1:	Summary of monthly climatological observations data taken at 09.00 hrs at AgResearch and Aorangi Research stations close to study sites.	31
Table 3.2:	Selected soil characteristics of the fields at the Kairanga site.	32
Table 4.1:	N ₂ O emission rates using the exploratory samples in the pilot experiment.	47
Table 4.2:	Effect of time of analysis on N ₂ O emissions following collection of gas samples from the field.	48
Table 4.3:	N ₂ O emissions from 12 chambers measured to determine baseline variation.	48
Table 4.4:	Comparison of N ₂ O fluxes before (March 17) and after (March 18) power harrowing in the CT treatment at the Massey site.	49
Table 4.5:	Ohakea silt loam soil pH, total C and total N of the Massey experimental site.	52
Table 4.6:	The effects of tillage systems on the ranges of N ₂ O emissions from Massey plots.	54
Table 4.7:	The effects of tillage systems on the means of N ₂ O emissions from Massey plots.	54
Table 4.8:	Effects of tillage systems on the monthly means of N ₂ O emissions data at Massey site (December 1998 to September 1999).	56

Table 4.9:	Effects of tillage systems on the monthly means of log transformed N_2O emissions at Massey site (December 1998 to September 1999).	57
Table 4.10:	Effect of tillage techniques on soil moisture content at 0-10 cm depth during N_2O emission measurements.	62
Table 4.11:	Seasonal field N_2O emissions as affected by the PP, CT and NT treatments.	65
Table 4.12:	The effects of tillage systems on the ranges of N_2O emissions from Kairanga plots.	68
Table 4.13:	The effects of tillage systems on the means of N_2O emissions from Kairanga plots.	69
Table 4.14:	Effects of length of continuous cropping and permanent pasture on the mean monthly N_2O emissions at the Kairanga site (November 1998 to September 1999).	70
Table 4.15:	Effect of length of continuous cropping and permanent pasture on the mean of log-transformed monthly N_2O emissions at Kairanga site (November 1998 to September 1999).	71
Table 4.16:	Soil moisture content at 0-10 cm depth during N_2O emission measurements.	76
Table 4.17:	Correlation of soil moisture content with N_2O emission rates at the Kairanga field site.	79
Table 4.18:	Seasonal log-transformed field N_2O emissions in the PP, CT and NT treatments.	80

List Of Figures

Figure 2.1	Simplified diagram of nitrogen transfers, removals and losses of the agro-ecosystem. (Winteringham, 1984)	5
Figure 2.2	Nitrous oxide measurements at Cape Grim, Tasmania (up to 1995), and at Baring Head from 1995 onward. (NIWA report)	10
Figure 2.3	Estimates of the relative net cumulative warming effect over 100 years of New Zealand's anthropogenic emissions of each of the major greenhouse gases as measured in 1995. (Ministry for the Environment, 1998)	11
Figure 3.1	Kairanga site 34 years (K34) treatment field.	33
Figure 3.2	Permanent pasture (PP) field treatment at Kairanga site.	33
Figure 3.3	Massey site experimental treatment plots.	35
Figure 3.4	Schematic layout of experimental treatment design plots at Massey site.	36
Figure 3.5	Closed cover chamber used to collect field nitrous oxide (N_2O) emissions.	41
Figure 3.6	Installed chamber fitted with 3-way tap for withdrawing air samples using syringe.	45
Figure 3.7	Injecting 10 ml of gas sample into gas chromatography (GC) instrument to measure nitrous oxide (N_2O) concentration.	45
Figure 4.1	Increase in N_2O concentration in a closed chamber over time in the treatments: (a) conventional tillage (CT); (b) no-tillage (NT); (c) permanent pasture (PP). (bars represent standard error)	51
Figure 4.2	The effect of tillage treatment of the PP, CT and NT on the monthly data of soil moisture (a), temperature (b) and log-transformed means of N_2O emissions (c).	60
Figure 4.3	Regression analysis between measured soil moisture content and N_2O emissions in the PP (permanent pasture), CT (conventional	63

tillage) and NT (no-tillage) treatments.

- Figure 4.4 Regression analysis of log-transformed data between soil moisture content and N_2O emissions in the PP (permanent pasture), CT (conventional tillage) and NT (no-tillage) treatments. 64
- Figure 4.5 Monthly rainfall data for the Massey site from December 1998 to September 1999 and 1996-97, 1997-98. 66
- Figure 4.6 The effect of tillage treatment of the PP (permanent pasture), K17 (17 years continuous maize) and K34 (34 years of continuous maize) on the monthly data of soil moisture (a), temperature (b) and log-transformed means of N_2O emissions (c). (bars represent LSD) 75
- Figure 4.7 Regression analysis between measured soil moisture content and N_2O emissions in the PP (permanent pasture), K17 (17 years of continuous maize) and K34 (34 years of continuous maize) treatments. 77
- Figure 4.8 Regression analysis of log-transformed data between soil moisture content and N_2O emissions in the PP (permanent pasture), K17 (17 years of continuous maize) and K34 (34 years of continuous maize) treatments. 78
- Figure 4.9 Monthly rainfall data for the Kairanga site from November 1998 to September 1999, 1996-97 and 1997-98. (note: rainfall data for 97-98 was used from another station located in close proximity) 81

Chapter 1

General Introduction

There is a growing concern world-wide about climate change. Atmospheric warming which is known to be caused by so-called “greenhouse gases” mainly include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) and to a lesser extent chlorofluorocarbons (CFCs) (IAEA, 1992). Presently, the increase in greenhouse gases other than CO_2 in changing the climate is similar in importance as CO_2 . One such gas is N_2O which despite its low concentration in the atmosphere, about 310 ppb (IPCC, 1995), on a molecule per molecule basis has a radiative force about 200 to 300 times that of CO_2 (Jaques, 1992) and an average atmospheric lifetime of about 150 years (IAEA, 1992). It is widely accepted that the main source of N_2O is agriculture.

Most N_2O originates with soil processes, as intermediate product from microbial nitrification and denitrification (Delwiche, 1981). Increased emissions of N_2O from soils are associated with fertilisation of soils with mineral nitrogen (N), animal manure, N derived from biological N_2 fixation, and enhanced N mineralisation (MacKenzie et al., 1998). With fertiliser usage predicted to grow worldwide at 6-7% per annum (Peoples et al., 1995) and low N utilisation efficiency in agricultural systems, the potential of soils to form and emit N_2O increases. This increased N_2O emission to the atmosphere is of great concern and need quantification.

Amounts of N_2O emitted depend on complex interactions between soil properties, climatic factors and agricultural practices (Granli and Bockman, 1994). Main factors in the soil controlling N_2O emissions are soil content of NH_4 and NO_3 (Ball et al., 1997; Castaldi and Smith, 1998; Seneviratne and Van Holm, 1998); soil aeration status and soil water content (Carran et al., 1995; Teira-Esmatges et al., 1998; MacKenzie et al., 1998); presence of degradable organic material which promotes microbial activity (Ineson et al., 1998; Kaiser et al., 1998); soil pH (Anderson and Poth, 1998; Sitaula and Bakken, 1993; Burth and Ottow, 1983) and soil temperature (Mahmood et al., 1998). Although these are known interacting factors they are not always strongly correlated with N_2O fluxes. Due to complexity of interactions between various factors, N_2O emissions have very high spatial and temporal variations.

Agricultural practices alter soil properties which influence the extent of N_2O emissions. Intensive use of cultivation practices, both internationally and locally in New Zealand, hugely impact soil properties. In the Manawatu region heavier textured soils used for continuous maize production result in loss of soil organic matter (SOM) (Saggar et al., 2000) and deterioration in soil structure (Shepherd et al., 2000). Even short term tillage operations can affect SOM levels and microbial biomass (Aslam et al., 1999) which are of particular interest in nutrient transformations. Conversion of pastures to arable cropping in New Zealand results in depleting of SOM and soil fertility over time and additional N fertilisers are applied to compensate for the loss of organic N reserves.

Since N fertilisation is considered as a major practice on increasing N_2O emission from soil by providing an additional N source (Ryden and Rolston, 1983), careless N application on such soils may contribute to increased loss of N either as NO_3 through leaching or as N_2O emissions.

An alternative to conventional tillage system is conservation tillage system which aims for sustainable agricultural production. Its growing acceptance is due to reduced soil erosion and runoff (Choudhary et al., 1993; Unger and Vigil, 1998; Myers and Waggoner, 1996), enhanced moisture retention and infiltration (Baumhardt and Lascano, 1996), lower summer temperatures (Prihar et al., 1996) and possible increased net return to the farmer (Reicosky, 1994). However, the impact conservation tillage has on N_2O emission is not known for these Manawatu soils.

In the past 20 years, research of N_2O emissions has concentrated on enhancing an understanding of N_2O production processes and its controlling factors. Despite this it is not possible to predict the fate of a unit of N that is applied on a specific arable field (Mosier et al., 1996). Both short- and long-term in-situ measurements are needed to assess N_2O emissions from soils.

Studies by Ruz-Jerez et al. (1994) and Carran et al. (1995) from both poorly and well drained grazed pastures in the Manawatu region suggest low N_2O emission from these low fertility hill lands. However, there is little information for arable farming systems. Therefore, there is a need for site-specific assessment of the impact of tillage practices on N_2O fluxes.

1.1 Research Objectives

To evaluate long-term and short term impacts of different tillage systems and land use on N_2O emissions selected farming practices were chosen in the Manawatu region of New Zealand. The overall aim was to characterise land use practices and their effect on N_2O emissions. This study is a part of a wider project on soil nitrogen recycling.

The specific objectives of this study were as follows:

- To quantitatively determine the rates of N_2O emissions from fields sown with the conventional tillage (CT), no-tillage (NT) and compare these with permanent pasture (PP) fields throughout one management cycle.
- To measure the response of soil N_2O emissions to various cultural practices and selected environmental parameters such as changes in soil moisture and soil temperature.
- To measure soil physical and chemical properties and assess their interactions with N_2O emissions.

Chapter 2

Literature Review

2.1 Introduction

This literature review addresses the global impact of changes in land use and soils as a presently known major source of anthropogenic N_2O and discusses issues and possible ways of reducing N_2O emission into atmosphere.

Human interference in the land cover has brought changes in the environment. Modern agricultural practices, such as monocultures with limited return of crop residues to the soil and the use of chemical fertilisers, have been reported to cause severe soil degradation. Agricultural conversion disrupts the steady state conditions that exist in many natural conditions (Bouwman, 1990).

The increase in concentration of a number of atmospheric gases has been having alarming global impact due to human activities. These gases include carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), nitrogen oxides (NO_x) and ammonia (NH_3). Possible causes of the increase in the concentration of these gases are the increasing emissions by the various sources and in some cases a reduced sink capacity (Bouwman, 1990). Bouwman (1990) has summarised data on the annual rise in the concentration of important gases, heat absorbing capacity and the contribution to the global temperature rise which occurred during the past 100 years (Table 2.1).

N_2O oxide is one of the “greenhouse gases” which forms part of the nitrogen cycling (Figure 2.1) which is involved in a number of atmospheric processes. Moreover, its reaction products are known to cause substantial changes in stratospheric processes. Soils are known major source of the enhanced emission of N_2O while other sources have minor inputs to global emission. Release of N_2O from soils is known to occur during biological denitrification, chemical denitrification and nitrification.

Reported values of measured N_2O emissions often reflect high variability. There are some already known factors which control N_2O fluxes but they are not always primary ones. The potential of a soil to form and emit N_2O increases with increasing availability of N, but the actual amounts emitted depend on interaction between controlling factors.

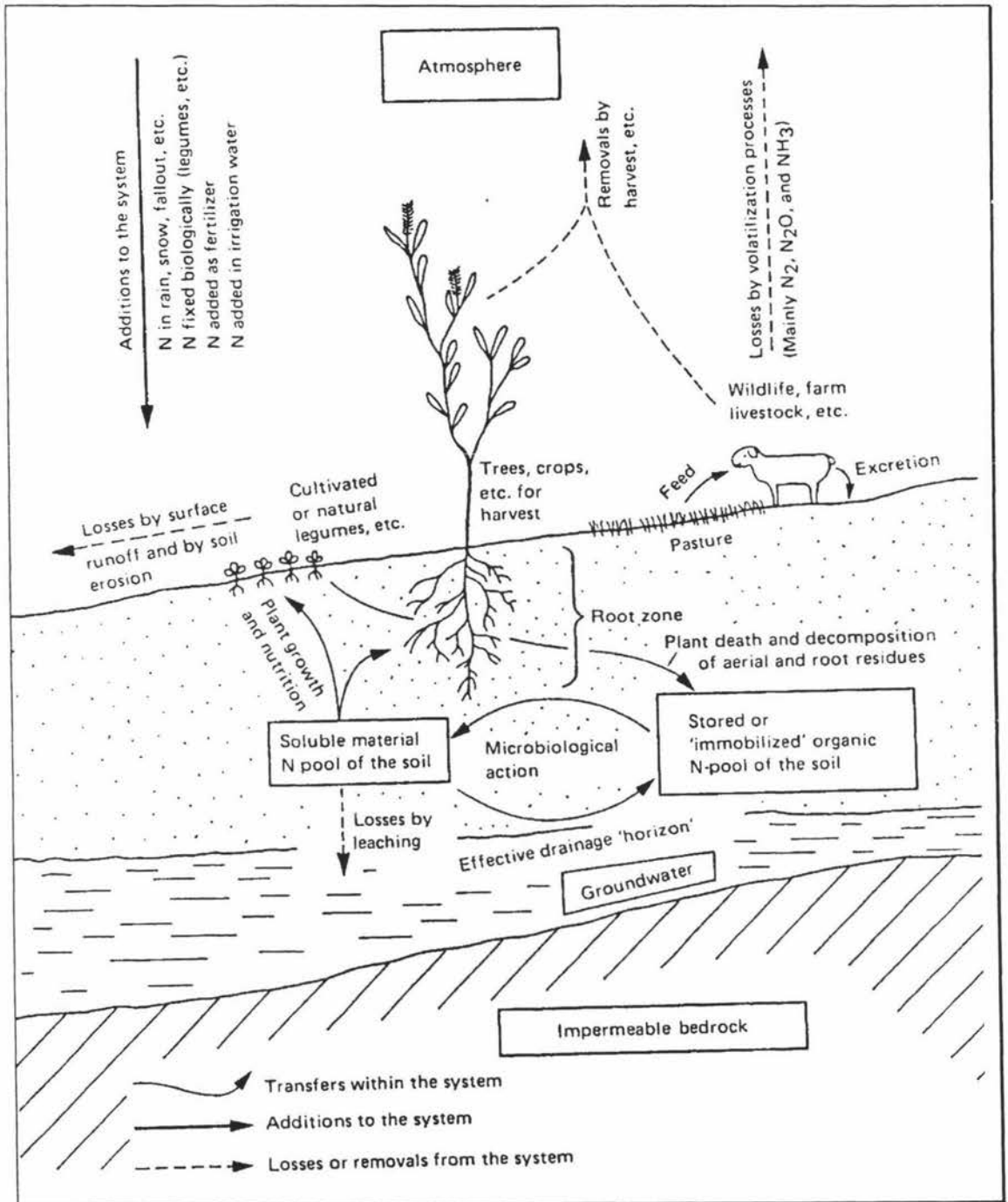


Figure 2.1 Simplified diagram of nitrogen transfers, removals and losses of the agro-ecosystem. (Winteringham, 1984)

Table 2.1: Atmospheric concentrations of the major greenhouse gases, their rise, residence time and contribution to the global warming

Type	Residence time (years)	Annual Rise (%)	1985 concentration	Radiative absorption potential	Contribution to greenhouse warming (%)
CO ₂	100	0.5	345 ppm	1	50
CO	0.2	0.6-1.0	90 ppb	n.a.	n.a.
CH ₄	8-12	1	1.65 ppm	32	19
N ₂ O	100-200	0.25	300 ppb	150	4
O ₃	0.1-0.3	2.0	n.a.	2,000	8
CFCs	65-110	3.0	0.18-0.28 ppb	>10,000	15

** Bouwman (1990)*

2.2 Nitrous Oxide in the Atmosphere

N₂O is capable of absorbing infrared radiation, but it is inert in the troposphere. According to an IPCC (1995) report the mean estimated atmospheric concentration of N₂O in 1990 was 310 ppb, corresponding to a reservoir of about 1500 TgN. Reports have put its increasing rate at approximately 0.2-0.3% per year and the observed rate of increase represents an atmospheric growth rate of 3 to 4.5 TgN per year.

2.3 Sources of Nitrous Oxide

N₂O oxide is formed from various sources but in general they can be divided into two categories: natural and anthropogenic. Natural sources include soils, oceans, fresh waters, fires, lightning, and vegetation. The fluxes from soils and marine waters are the dominant global sources of N₂O (Jaques, 1992). Part of the N₂O emission from water ecosystems originate from ground water which is supersaturated with N₂O originating from soil microbial processes (Granli and Bockman, 1994). Soil microbial processes are generally regarded as the major global source of N₂O. The increased emissions of N₂O from natural sources are also partly caused by human activities which probably enhanced N₂O formation in natural ecosystems.

N₂O oxide is produced directly from the burning of fossil fuels, although the mechanisms that cause N₂O formation are not completely understood. Biomass burning

including forest cleaning, savanna and sugar cane field fires, burning of agricultural waste and firewood is another possible source of N_2O . Some N_2O is formed during the processes involved in manufacturing of nitrogen fertilisers and production of nylon, plasticisers and industrial chemicals (Jaques, 1992).

There are other minor sources which release N_2O . They include anaesthetic usage, propellant usage, high voltage transmission lines and other minor miscellaneous sources. In general, all environments where nitrogen compounds are transformed by biological processes are potential sources of N_2O .

Major agricultural practices influence N_2O emissions (Mosier et al., 1997; Kessavalou et al., 1998b; Aulakh et al., 1984) and estimated that they may contribute approximately 70-90% of anthropogenic N_2O emission. Fertiliser applied soils can emit N_2O under either anaerobic or aerobic conditions. Studies show that soils have increased potential of emitting N_2O depending on fertiliser types applied (Bremner et al., 1981). These authors have reported that the fertiliser-induced emissions of N_2O observed after application of anhydrous ammonia greatly exceeded those detected in similar field studies using other N fertilisers and represented 4 - 6.8% of the fertiliser N applied.

Chang et al. (1998) reported that under high N_2O producing conditions, generally characterised by a high soil moisture content and concentrations of N_2O in soil solution and groundwater, low gas diffusion rate, emissions from plants may even exceed those from the soil surface during periods of high transpiration.

2.4 Impact of Nitrous Oxide on the Environment

Two main concerns with increasing emissions are the processes which enhance N_2O emissions.

1. N_2O oxide contributes significantly to the atmospheric “greenhouse” effect by trapping outgoing terrestrial radiation (Crutzen, 1981). N_2O is essentially transparent to incoming short-wave solar radiation but it absorbs and emits longwave radiation which influences the Earth’s climate (Bolin et al., 1986).

2. Nitrogen oxides produced from N_2O by photochemical reactions in the stratosphere are involved in destruction of stratospheric ozone. Stratospheric ozone layer shields the biosphere from harmful UV radiation and influences the vertical temperature profile and thus earth surface temperatures.

Direct transport of NO_x into the stratosphere from the earth's surface is unlikely because of the short atmospheric residence time of NO_x , which is quickly converted to HNO_3 aerosols and thermally unstable organic nitrates and removed by wet and dry deposition (Crutzen, 1981).

One of the major sinks of O_3 is a reaction with NO_x , which catalyses the destruction of O_3 above 25 km in the stratosphere (Crutzen, 1981). However, Delwiche (1981) alerts that NO_x also react with degradation products from volatile chlorinated carbon compounds and thus diminish their ability to cause ozone destruction. The influence of N_2O on the stratospheric ozone shield is thus complex. However, slowly increasing atmospheric N_2O concentration may have an over-all detrimental effect on the total ozone content of the stratosphere (Granli and Bockman, 1994).

2.5 Global Nitrogen Perspective

Nitrogen (N) in the environment is reviewed from distribution and cycling of N which have been discussed in detail by Haynes (1986). Gaseous N in the atmosphere represents only 1.9% of earth's total N mass and the rest 98% is held in rocks and minerals. Haynes (1986) summarised the biogeochemical distribution of N on Earth as shown in Table 2.2.

The magnitude of the global flows of N due to some of the processes illustrated in Figure 2.1 is shown in Table 2.3. The major additions of N to the soil occur through the processes of wet and dry deposition and by the action of micro-organisms that fix atmospheric N_2 . Man is increasingly active in fixing N_2 , by industrial processes and by use of internal combustion engines. In many areas, most nitrates in precipitation originate from sources related to man. The quantity of N fixed industrially and applied to agricultural lands is of the same order as that fixed by micro-organisms (Table 2.3).

Losses of N occur through leaching of NO_3 , erosion and surface runoff, volatilisation of ammonia, gaseous losses of N_2 and N_2O , and, in agricultural ecosystems, plant or

Table 2.2: Biogeochemical distribution of N on Earth

Pool of nitrogen	Total mass (Tg N)	Percentage of total N mass (%)
Atmosphere N_2	3.9×10^9	1.9
N_2 dissolved in oceans	2.2×10^7	0.01
Biosphere	2.4×10^7	0.01
Lithosphere		
Igneous rocks	1.9×10^{11}	97.8
Sedimentary rocks	4.0×10^8	0.2
Total N mass	1.94×10^{11}	

* compiled by Haynes, 1986

Table 2.3: Global fluxes of nitrogen into and out of the terrestrial biosphere

	Process rate (Tg N year ⁻¹)
Inputs	
Wet and dry precipitation (NH_3/NH_4)	90-200
Wet and dry deposition (NO_x)	30-80
Wet and dry deposition (organic N)	10-100
Atmospheric fixation (lightning)	0.5-30
Biological fixation	100-200
Industrial fixation	60
Outputs	
Ammonia volatilisation	36-250
Denitrification ($\text{N}_2 + \text{N}_2\text{O}$)	40-350
Biogenic NO_x production	1-15
Fossil fuel burning (NO_x)	10-20
Fires (NO_x)	10-20
Leaching and runoff (inorganic)	5-20
Leaching and runoff (organic)	5-20

* compiled by Haynes, 1986

animal removal. Although Table 2.3 shows the greatest N_2O and N_2 loss through denitrification, N_2O emission can occur as a result of two separate processes: denitrification and nitrification.

When a natural ecosystem is in a steady state (e.g., a mature forest) the rate of N input by precipitation and biological N_2 fixation balances outputs by denitrification, volatilisation, and groundwater and storm loss. However, when natural ecosystems are disturbed the N cycle is interrupted because of removal of vegetation.

Agricultural ecosystems often have a greater N requirement than natural ecosystems. While much of the N used by crop plants is harvested and removed from the ecosystem fertiliser additions are widely believed to have enhanced soil N_2O emissions.

2.6 Status of Nitrous Oxide Emissions in New Zealand

National Institute of Water and Atmospheric Research (NIWA) has made trace gas measurements at Baring Head (on the South Coast of the North Island near Wellington)

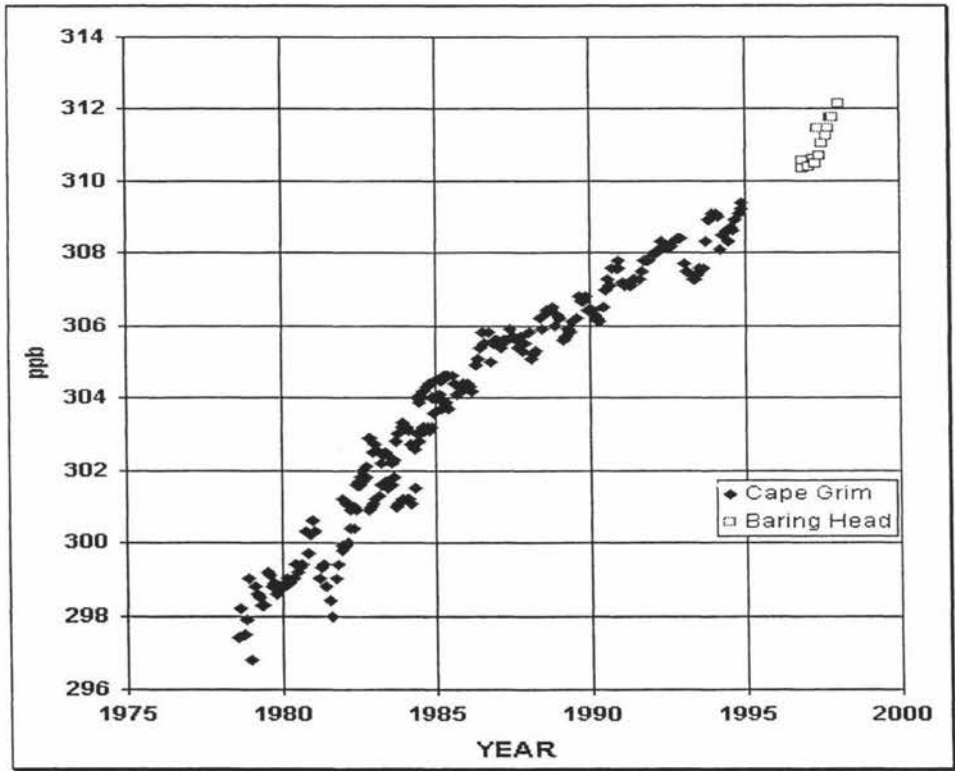


Figure 2.2 Nitrous oxide measurements at Cape Grim, Tasmania (up to 1995), and at Baring Head from 1995 onward. (NIWA report)

(Figure 2.2) since 1973. The measurements contribute to the global network for determining trends in greenhouse gas concentrations. Figure 2.2 shows a steady increase in N₂O levels at Cape Grim, Tasmania and Baring Head from 1970s to the present.

Although N₂O emission measurements are still rather uncertain due to high spatial and temporal variations they contribute almost 20% of New Zealand’s total greenhouse gas loading (in relation to carbon dioxide) and all of this is from land-based industries (Figure 2.3) (Ministry for the Environment, 1998).

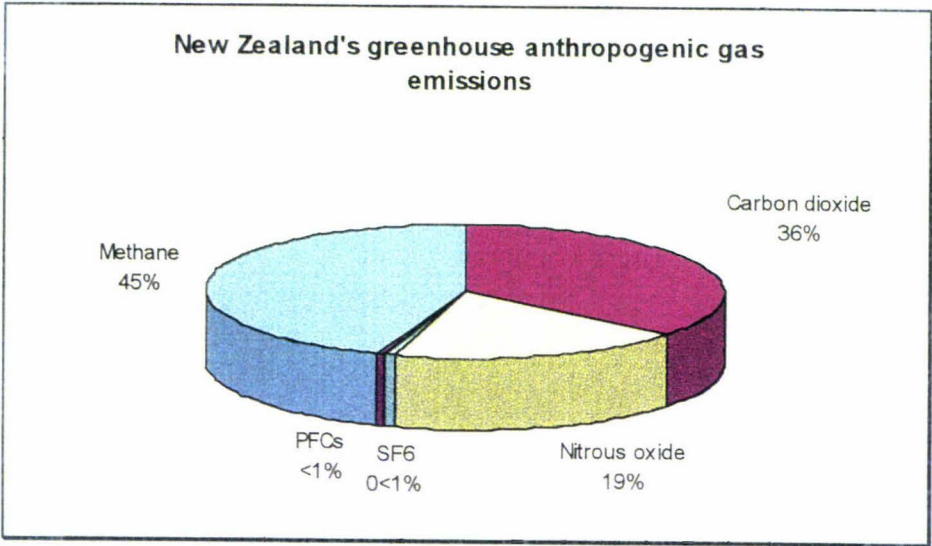


Figure 2.3 Estimates of the relative net cumulative warming effect over 100 years of New Zealand’s anthropogenic emissions of each of the major greenhouse gases as measured in 1995. (Ministry for the Environment, 1998)

In New Zealand context, Carran (unpublished) states that nitrogen fertiliser use clearly increases N₂O emission, but it largely depends on how long soils remain wet. In well-drained soils and low rainfall areas, N₂O production is low, but can increase up to 5-7 kg N/ha in poorly drained soils receiving moderate to high rainfall. The highest values recorded locally have been on wet, poorly drained soils during grazing by mobs of dairy cows that caused serious pugging (Carran et al., 1995).

Although the steps to reduce emissions are not clear Carran (unpublished) suggests that drainage may have a positive effect in reducing N₂O emission, whereas irrigation and nitrogen fertiliser can have a negative effect.

2.7 The Role of Micro-organisms

Biotic sources of N_2O have been explained by Umarov (1990). Micro-organisms are the main biotic sources of N_2O in terrestrial and aquatic ecosystems. Numerous bacteria can denitrify in anaerobic and aerobic conditions while only highly specialised bacteria can nitrify in specific ecological conditions (e.g. pH nearly neutral, sufficient aeration, lack of organic matter, low concentration of ammonia).

The formation of N_2O in natural conditions is caused by the ability of all organisms for oxidation and reduction of nitrogen in different mineral and organic compounds. Micro-organisms are capable of oxidation and reduction of all nitrogen compounds producing N_2O among other products. Formation and consumption of N_2O are carried out by large groups of heterotrophic and autotrophic micro-organisms. Most of them are bacteria, but there are some eucaryotic organisms, especially fungi, which are able to produce N_2O (Umarov, 1990).

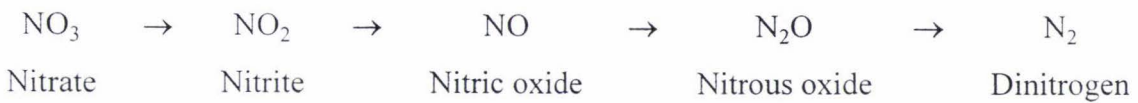
2.8 Mechanisms of Nitrous Oxide Production

Release of oxides of nitrogen (N_2O , NO and NO_2) from soils is known to occur during biological denitrification, chemical denitrification and nitrification. Denitrification and nitrification are two microbial processes which contribute most to the emissions of N_2O from soils.

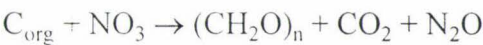
Initially, N_2O was thought to originate largely through denitrification process. However, other research studies have indicated that some of N_2O may be produced through nitrification. Works reported by Bremner and Blackmer (1981) and Mosier et al. (1983) show that nitrification also can be a significant source of N_2O . The relative importance of these processes varies with local circumstances.

2.8.1 Denitrification

Denitrification is a form of anaerobic bacterial respiration during which nitrogen (N) oxides, principally nitrate and nitrite, are reduced sequentially through NO and N_2O to N_2 (Aulakh et al., 1992). The commonly accepted reductive pathway for denitrification is as follows:



Denitrification occurs when soil is starved of oxygen (e. g., under conditions of temporary flooding by heavy rain, irrigation controlled flooding of rice paddy, etc.) (IAEA, 1984). During this anaerobic process, nitrate serves as an electron acceptor for the oxidation of organic (and sometimes inorganic) compounds, with the yield of energy and the release of gaseous N_2 . The majority of soil bacteria seem to be able to denitrify but they exhibit variety of incomplete reduction pathways (Umarov, 1990).



According to Umarov (1990) ecological factors, such as nitrate concentration, level of aeration, temperature and pH have secondary significance. They affect only the denitrifying potential, but the actual activity of the process is only affected in the presence of sufficient organic matter.

Depending on soil conditions, intermediate products (NO and N_2O) can accumulate and eventually escape from the soil before being reduced. The ratio of N_2 to N_2O in the gases evolved from soil (approximately 16:1) depends on such factors as soil pH, moisture content, redox potential (E_h), temperature, nitrate concentration and content of available C (IAEA, 1984).

The N_2O emissions from denitrification are normally short-termed, episodic events occurring during the initial development of soil anaerobiosis (Byrnes et al., 1990). Although denitrification may be discounted as a source of N_2O under the well-aerated soil conditions of the tropical dry season, it may be important during the rainy season (Anderson and Poth, 1998).

2.8.2 Nitrification

Nitrification is classically defined as the process whereby NH_4 is oxidised via NO_2 to NO_3 . The reactions are generally mediated in soil by activities of two small groups of chemoautotrophic bacteria. One group, the NH_4 oxidisers, initiates the process with the formation of NO_2 , while a second group, the NO_2 oxidisers, completes the process by

converting NO_2 to NO_3 as promptly as it is formed (Haynes, 1986). Autotrophic nitrifiers use CO_2 as a carbon source and obtain their energy by oxidation of NH_4 (Umarov, 1990).

There are two possible ways in which N_2O gas is evolved during the process. The presumed intermediate NOH , or its dimer hyponitrite, may dismutate chemically under reduced O_2 tensions to N_2O or the dissimilatory enzyme system, nitrite reductase, may yield N_2O when O_2 becomes limiting and NO_2 replaces O_2 as an electron acceptor (Schmidt, 1982).



Alternatively NO and N_2O can also be produced abiotically by reduction of NO_2 , especially when soil pH is low. In aerobic soils both NO and N_2O are most likely produced directly or indirectly by nitrification.

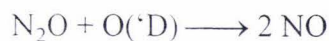
N_2O produced during nitrification has a greater probability of being lost from the soil than does N_2O produced during denitrification. Because soil pores are generally open during nitrification and diffusion is allowed to the soil surface, there is less water present to dissolve N_2O . In contrast to denitrification, emissions during nitrification in soils are relatively constant and may actually decrease temporarily following rainfall (Byrnes et al., 1990).

Davidson et al. (1993) reported that nitrification was the dominant source of N_2O when the soil was wetted at the end of the dry season, and that denitrification might be an important source of N_2O during the wet season. These results support a conceptual model in which N trace gas production is generally constrained by the rates of N mineralization and nitrification, while the specific ratios of NO and N_2O fluxes and the contributions from nitrifying and denitrifying bacteria are controlled largely by soil moisture.

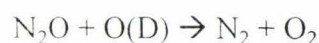
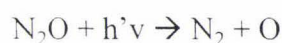
2.8.3 Sinks

Reaction of N_2O in the stratosphere is perhaps regarded as the only significant process for removal of N_2O from the atmosphere. Crutzen (1981) explains in details that

electronically excited $O(^1D)$ atom is produced by photolysis of ozone in the stratosphere. Approximately 10% of stratospheric N_2O is thought to be converted to nitric oxide by the reaction



NO then participates in further reactions with ozone and other reactive molecules. Two additional reactions in the stratosphere contribute to the removal of N_2O from the atmosphere:



Soils can act as a sink too. In soil denitrification process, whether nitrate is converted to N_2 gas or N_2O , it is no longer readily available to plants, and only a limited number of micro-organisms (or micro-organisms in association with plants) are capable of “fixing” atmospheric nitrogen and bringing it back into the biological cycle (Delwiche, 1981). A number of studies observed negative emissions of N_2O (Teira-Esmatges et al., 1998). The observed emissions of N_2O were the result of two counteracting phenomena: the emission of N_2O from the soil and consumption of headspace N_2O by the soil (Van Cleemput et al., 1994). According to these authors the emission from the soil depends on:

- (i) the formation of N_2O during denitrification and during nitrification, and its diffusion to the headspace.
- (ii) the consumption of N_2O through its reduction to N_2 during the denitrification and the diffusion rate of N_2O from the headspace into the soil. When N_2O consumption was larger than its emission, the N_2O concentration in the headspace decreased resulting in negative fluxes of N_2O .

Similar findings were recorded by Mahmood et al. (1998) who observed N_2O sink activity during the maize and wheat season on one third of sampling occasions which ranged between 0.01 and 0.94 g N ha⁻¹ h⁻¹. The generally low N_2O mole fraction of the gaseous N products of denitrification and frequently observed negative N_2O fluxes

indicated that the soil conditions under irrigated maize and wheat were favourable for N_2O reduction.

Few studies have suggested that plants also acted as a sink. For example, Grundmann et al. (1993) demonstrated that $^{15}\text{N}_2\text{O}$ accumulation in the jars was lower in the presence than in the absence of plants. The authors also stated that $^{15}\text{N}_2\text{O}$ was taken up by maize leaves and metabolised as a source of N. Acceptance of this process as a possible N_2O sink and N source in natural environment requires independent confirmation and quantification.

2.9 Agriculture as a Major Source of Nitrous Oxide Emissions

Man has changed steady-state conditions of the environment in the last century. This in turn has negatively affected the environmental processes. The extent of cultivation practices has increased nitrogen cycle through soil disturbance and the amounts of fertiliser put into soils. In terms of N_2O emission soil disturbance decreases fluxes due to better aeration, however the amounts of fertiliser applied into cultivated soils increases potential emissions of N_2O .

2.9.1 Effects of Tillage Practices

Research has shown that conversion of 'native' grass sod significantly increased net soil N_2O emissions compared to wheat-fallow cropping (Kessavalou et al., 1998b). More detailed study of the effects of conversion was conducted by Mosier et al. (1997) who also found that conversion of grassland to croplands typically increased the emission of N_2O . Although N_2O fluxes were about 8 times higher for 18 months following ploughing, the relative rates declined to 25-50% higher than the native site after 3 years. N_2O emissions 2 years after ploughing were similar to the grasslands converted to a winter wheat-fallow production system about 70 years ago (Mosier et al., 1997).

The authors found that reversion of cultivated soils that had been cultivated in the early decades of 20th century back to grasslands eventually lead to soils having similar N_2O emissions to those of native soils of the same texture and parent material. Sites that were last ploughed in 1939 exhibited the same N_2O flux rates as comparable never-tilled soils during 15-month measurement period. They concluded that it requires from 8 to 50

years following tillage to return to N_2O emission rates observed in the native state in shortgrass steppe.

In contrast, conservation practices aimed at reducing harmful effects of extensive conventional practices contributing to N_2O emissions through improved soil conditions, such as increased soil organic matter, higher soil microbial biomass, and moisture content, all of which are favourable conditions for enhanced formation and emissions of N_2O .

A number of reports indicate that no-till has higher emissions rates compared to conventionally managed lands. The hypothesis that the extra C going below-ground may stimulate N_2O production by soils (as a consequence of enhanced root-derived available soil C, acting as an energy source for denitrification) gave positive results (Ineson et al., 1998).

Colbourn (1988) observed denitrification in the undrained ploughed soil as one-fifth of that in undrained direct-drilled soil. Cultivation restricted denitrification to a greater extent than drainage. In drained soil it was restricted to one-twelfth by ploughing. The authors attribute differences in denitrification to the denitrification in soil structure caused by the soil systems. In particular the direct-drilled soils both (drained and undrained) behaved similarly despite differences in drainage, but very differently to the ploughed soils.

The lack of soil disturbance with reduced tillage leads to a reduction in large pores, increased soil aggregation and reduced soil aeration. Populations of bacteria responsible for N_2O production may also be greater under no-till management.

MacKenzie et al. (1998) associated higher N_2O emissions in the NT systems, with corn compared to other crops, to increased crop residue C and inorganic N from higher N input from fertilisation. However, there are several alternatives that can be implemented to reduce N_2O emissions from the soil surface.

2.9.2 The Role of Fertilisers

Increased nitrogen fertiliser use is considered to having substantial impact on N_2O

despite small percentage of it being lost as a N_2O . The main reason is that fertiliser application potentially enhances N_2O fluxes from the soils. Swensen and Bakken (1998) demonstrated that urea enhanced growth of nitrifying bacteria in mineral subsoil. The authors hypothesised that bacteria recovering from starvation or restricted activity after adding urea had higher production of N_2O . Similar findings by Seneviratne and Van Holm (1998) were made where urea application resulted in a 4-fold increase in N_2O emission from the soil.

Studying the effects of three N fertilisers (urea, ammonium sulphate, and calcium nitrate) on emissions of N_2O from soil Breitenbeck et al. (1980) showed that the emissions of N_2O induced by application of urea or ammonium sulphate markedly exceeded those induced by application of calcium nitrate. The emissions, however, represented <0.2% of the fertiliser N. Similar study with anhydrous ammonia by Bremner et al. (1981) found that this fertiliser-induced emissions of N_2O greatly exceeded those detected using other N fertilisers and represented 4.0-6.8% of the fertiliser N.

Gaseous losses of fertiliser applied N are generally less than 5% (Kaiser et al., 1998, MacKenzie et. al., 1998) but other studies have reported losses of up to 13.6% (Teira-Esmatges et. al., 1998). This could be due to the kinds of soil micro-organisms involved in the transformations of soil N and subsequent N_2O emissions.

These were demonstrated by Castaldi and Smith (1998) where different forms of N had very different impacts on N_2O emissions in the two light textured soils, suggesting the involvement of different microbial communities in the N_2O production in arable and woodland soils. The arable soil had a very low potential for N_2O emissions derived from nitrifiable N, as compared with the N_2O which was produced when the soil was provided with nitrite and nitrate and a carbon source. That is the likely reason of different fertiliser gaseous losses.

2.10 Factors Controlling Nitrous Oxide Emission

2.10.1 Soil Properties

N_2O emissions are reported to be strongly influenced not only by land use and

management practices but also by a wide range of soil factors. For example, experiments conducted by Byrnes et al. (1990) indicated that emissions of N_2O during nitrification may be more dependent on the soil to which fertiliser is applied than on the fertiliser type.

N_2O fluxes generally depend on physical, chemical, and biological attributes of soil and on complex interactions between them. Fine-textured soils seem to emit more N_2O than coarse-textured ones, but this tendency can be masked or reversed by other factors, especially the soil water content. The clayey soils can have a higher potential for sustained N_2O formation than sandy soils, since clayey soils can maintain a higher water filled pore space (WFPS) for longer periods than can light, easily drained sandy soils. However, N_2O can escape more easily from coarse-textured soils. The resulting N_2O -N emission at the soil surface depends on the intensity of both the nitrification and denitrification processes (Teira-Esmatges et al., 1998).

Inherent soil properties very strongly influence the magnitude of annual N_2O emissions, masking the influences of management or climatic variability (Lemke et al., 1998b). These authors have suggested that large-scale spatial variability in the annual estimates of N_2O -N loss could be explained by differences in clay content, suggesting that this parameter could be an important criteria for stratification.

Christensen and Tiedje (1988) observed substantial nitrogen losses for a few days only on sandy soils, because they are flooded only for very brief periods. They also suggested that even in more clayey soils where flooding occurs for longer periods, excessive N losses might be of short duration due to consumption of the easily available carbon source.

The influence of soil texture on N_2O emission was generally studied in cases where denitrification prevails (Granli and Bockman, 1994). Denitrification of nitrate and nitrite is generally considered as the dominant source of N_2O in heavy textured soils, where oxygen diffuses more slowly than in light textured soils.

Introducing the concept of ion exchange or fixation in kinetic models on N_2O formation can increase knowledge on these processes in soils (De Visscher et al., 1998). The

authors suggest that N_2O formation can only be compared in soils with the same cation exchange capacity (CEC).

2.10.2 Soil Organic Matter

Denitrifying organisms use organic C compounds as electron donors for energy and for synthesis of cellular constituents, therefore, denitrification is strongly dependent on the availability of organic compounds such as native soil organic matter, crop residues, root exudates, and green and farmyard manure (Aulakh et al., 1992). Organic matter in soils is represented by plant debris or litter in various stages of decomposition through to humus and also includes microbial biomass (Bouwman, 1990). Concentrations of biomass C and organic C in the soil are highly correlated with denitrification activity (Drury et al., 1991), and there is evidence that increasing carbon availability decreases the N_2O fraction (Firestone, 1982).

Since organic matter in soils is represented by plant debris crop species have a significant influence on the N_2O emissions (Kaiser et al., 1998). The authors reported that the total N_2O losses during the winter increased with decreasing dry matter-to-N-content ratio of the plant residues incorporated into the soil by ploughing. Soil freezing and thawing greatly enhance the rate of denitrification by increasing the amount of soluble or readily available organic matter (Goodroad et al., 1984; Lemke et al., 1998a; Kaiser et al., 1998).

Denitrification is also enhanced in the presence of plants at least in upland soils. While part of this effect can be attributed to decreased oxygen availability the release of exudates in the rizosphere may contribute significantly to an enhanced rate of soil respiration by heterotrophic soil bacteria and concomitantly higher rates of denitrification where anaerobiosis develops (Aulakh et al., 1992).

There is hypothesis that elevated atmospheric CO_2 , by increasing plant productivity and enhancing allocation of C to below-ground components, may lead to a general increase of C input in soils. These influences can subsequently affect N_2O production. For example, roots may deplete available inorganic N and alter the soil physical status, resulting in decreased denitrification (Granli and Bockman, 1994). Ineson et al. (1998)

demonstrated the extremely high levels of N_2O production under elevated CO_2 conditions. The authors recorded 27% increase during their study which led to conclusion that elevated CO_2 may result in the increased output of N_2O , by providing excess available soil C, acting as an energy source for the process. Additionally, plants growing under elevated CO_2 may be subjected to greater N limitation because of the N being lost through denitrification.

2.10.3 Soil Moisture Content

Soil moisture may be a particularly important variable relative to N_2O emissions because of the strong seasonality of precipitation. Under climatic conditions, a period of drought reduces soil microbial activity in the summer whereas in the cool wet winters, activity is limited by low temperatures.

Denitrification rates generally increase with increasing soil moisture content which were observed by Sitaula and Bakken (1993) having a significant increase in N_2O accumulation by increasing the moisture content from 35 to 45%. Similarly, Carran et al. (1995) reported low or negligible N_2O emissions when the gravimetric soil water content was less than 35% in the Manawatu region, New Zealand. Above that apparent threshold, the upper level of emission values increased with water content.

When the soil is wetted N_2O will be produced more rapidly than it is reduced; if the soil dries fast enough, N_2O reduction to N_2 is prevented and rapid diffusion is possible (Bouwman, 1990). However, high soil moisture contents and poor soil structure favour denitrification but result in low N_2O fractions due to low air-filled porosity which reduces diffusivity of oxygen, resulting in more extensive anaerobic regions, and of N_2O , retarding N_2O escape and promoting its reduction to N_2 (Arah and Smith, 1990).

Mosier et al. (1981) showed brief peaks in the N_2O flux after precipitation events and Davidson et al. (1993) found large pulses of N_2O to additions of water to dry soil. This would indicate that N_2O production takes place close to the soil surface, where the essentially aerobic conditions are unlikely to favour denitrification (Bouwman, 1990). In contrast, Mosier and Parton (1985) report only low N_2O emission after rain events and Cates and Keeney (1987a) found no N_2O flux peaks following precipitation events

in three prairie soils. They attributed this to nitrification being the dominant process involved.

2.10.4 Soil pH

Nitrification, denitrification and dissimilatory NO_3 reduction to NH_4 (DNRA) are processes which can be intimately interlinked in aquatic environments at sediment-water interfaces. Stevens et al. (1998) studied effects of pH on N_2O emissions which were inconsistent. However, they observed highest N_2O fluxes at pH 6.5, and the minimum flux of N_2O occurred at pH 6.0 and 8.0. Similar trend was observed by Burth and Ottow (1983) where neutral conditions favoured the formation of larger proportions of N_2O .

Stevens et al. (1998) also showed that dissimilatory NO_3 reduction to NH_4 was occurring as well as denitrification particularly at higher pH values. At pH 8, NO_2 accumulated and there was a direct relationship between N_2O flux and NO_2 concentration. The authors stressed that many agronomic practices, such as liming, urea fertilisation and organic manure addition result in soil pH values > 6.5 at microsites so DNRA as process for N_2O production may be much more important than presently realised.

In the study of four denitrifying bacteria and soil fungus Burth and Ottow (1983) concluded that the quantity rather than the quality of gas production shows a marked dependence on the pH of the environment. The composition of the denitrifying gases is specific to the organisms in question (under given set of conditions). In soil or water, denitrification by fungi such as *Fusarium* spp. should not be underestimated, the more since the strain isolated proved to be highly effective in producing N_2O from nitrite at reduced oxygen pressure.

2.10.5 Temperature

N_2O emissions are highly variable and generally the amplitude of variation is greater at higher temperatures and with larger fertiliser doses (Bouwman, 1990). The effect of increasing soil temperature on denitrification rate has been investigated in many laboratory studies. Temperature has been found to have positive correlation with N_2O emission rates. The optimum temperature for the denitrification process is 25°C and

above, while the process is slow at 2°C. Denitrification is still rapid at elevated temperatures and will proceed to about 60 to 65°C but not at 70°C. In nitrification the optimum temperature lies between 30 and 35°C, while below 5°C and above 40°C the activity is very low (Alexander, 1977).

As temperature increases, the $\text{N}_2\text{O}/\text{N}_2$ ratio declines. Important losses may also occur at lower temperatures. Keeney et al. (1979) have reported, that while the rate of denitrification was low at temperatures below 15°C, the amount of N_2O (44-50% of the total gas production) was equivalent to that evolved at 25°C. Thus denitrification during the late autumn and early spring in temperate climatic zones could account for a significant portion of the N_2O released over the year, particularly as soils often tend to be saturated or at least have high moisture contents and consequently lower oxygen levels, over these periods as well.

2.11 Soil Management Practices Impacting Nitrous Oxide Emission

The fertiliser-induced emissions have been estimated as contributing from 5% to 25% of the total N_2O efflux on a global scale (Bolle et al., 1986). These emissions might be altered by technology or by policy decisions that could promote use of one fertiliser over another or use of a particular fertiliser management practice to reduce N_2O production (Byrnes et al., 1990).

Certain management practices can be encouraged to reduce or eliminate N_2O emissions. For example, in a study by Seneviratne and Van Holm (1998) emissions of N_2O was almost completely eliminated by the application of wet surface mulches, presumably either because of a decrease in the N_2O production in the soil with the mulch or due to an increase of N_2O consumption in the mulch or soil. The authors postulated that when a mulch is applied to a moist soil, micro-anaerobic conditions in the mulch can be formed due to moisture present and also due to the presence of a high amount of easily degradable organic matter resulting in the mulch forming a large oxygen sink. Those conditions may lead to the production of N_2O . In addition, the soil surface mulch may act as a barrier for N_2O emitted during soil denitrification and CH_4 produced in the moist soil. However, in this study, all plant materials used as mulches reduced the contribution to the enhanced greenhouse effect from the soil.

No-till systems are reported to have higher N_2O emission rates (MacKenzie et al., 1998) but benefits of this management practice cannot be compromised for detrimental effects of conventional tillage practices. Modelling assessment of US agriculture by Mummey et al. (1998) suggested that no-till management in areas that are relatively warm and wet may result in N_2O emissions similar to or less than conventional tillage and that no-till management may be a viable means to reduce N_2O emissions while increasing soil quality. However, the authors argue that even though initial conversion to no-till had greater N_2O flux it maybe short lived and simply the result of the non-equilibrium of the changing system. Over time as the crop surface residues increased the active fraction of the SOM, pool the N cycling may become tighter and less available to be converted to gas.

MacKenzie et al. (1998) suggested that corn system using conventional tillage, legumes in rotation, and reduced N fertiliser would decrease N_2O emission from agricultural fields. Low N_2O fluxes from grassland compared to tillage systems (Mosier et al., 1997) could also contribute to N_2O mitigation with additional benefits of restoration of soil properties. These would be especially suitable for unsustainable and deteriorated croplands.

New research into different forms of fertiliser N with coating or release rate is another direction of mitigation alternatives to control N_2O emissions.

2.12 Field Nitrous Oxide Emission Measurement Methods

Methods for field measurements of N_2O emissions from agriculture have been reviewed by Mosier (1990) and are described in a manual from the IAEA (1992).

The study of N_2O emissions from soils is complicated by experimental difficulties. The experimental methods can broadly be classified into field and laboratory studies. Comprehensive field studies provide the best basis for emission estimates, whereas laboratory studies can give valuable insight into the relative importance of factors affecting emissions (Granli and Bockman, 1994). Smith et al. (1994) summarised the N_2O fluxes measured by the various methods over the six consecutive days (Table 2.4).

Usually gas samples are taken and analysed in a laboratory. N_2O production can be precisely measured using gas chromatography (GC) and easily identified over relatively low atmospheric background concentrations (about 310 ppb). The precision of GC is sufficient for chamber methods and can also be used for micrometeorological stations when N_2O flux is adequate.

As a general rule, field N_2O flux samplings should preferably be done without any disturbance to the measured system. Currently, chamber methods are more readily available and inexpensive and used most often in studies reviewed. However, other methods such as micrometeorological, ultra-large chambers with IR spectrometer and soil air analysis are available.

2.12.1 Chamber Methods

Closed Chambers

N_2O in closed chambers is determined directly by measuring the short term buildup or decrease in concentration in a sealed enclosure placed over the land surface. Normally, flux chambers are simply inverted containers forming a trap for gases emitted from the soil (or water) surface, and from which gas samples can be removed at intervals to determine the rate of flux. They are usually relatively easy to construct from a variety of readily available materials which are inert for the gas of interest (IAEA, 1992).

Closed chambers can be divided into two types: fixed-base and removable.

- Fixed-base chambers are constructed with separate collars which are inserted into the soil for the duration of the experiment, and gas-tight chamber is attached for short period (Ambus and Christensen, 1994).
- Removable chambers are constructed as a one unit which are installed in the soil for a sampling time and then removed until next measurement date (Mosier and Hutchinson, 1981).

Both types are widely used. Fixed-base type offers less disturbance to the soil because once inserted collars can stay until the end of experiment. Also pressure change in the soil while inserting chambers is overcome by using collars. However, they do not

provide randomisation of chamber positions as opposed to the use of removable type and also can interfere with agricultural operations such as tillage.

Table 2.4: Comparison of flux measurements by flux gradient micro-meteorological, combined megachamber/long-path IR, and small chamber gas chromatograph (GC) methods.

Methods	N ₂ O Flux, ng N m ⁻² s ⁻¹					
	April 8	April 9	April 10	April 11	April 12	April 13
Eddy correlation micrometeorological TDL	ND	75-113	ND	ND	ND	38-48
Flux gradient micrometeorological TDL	ND	ND	20-70*	51-59	ND	ND
FTIR	47-103	0-127	34-55	ND	ND	ND
GC	45	35	ND	65	73-105	ND
Megachamber/long-path IR	ND	ND	247 (222-321)†	295 (266-384)†	ND	ND
0.126 m ² chambers within tent area/GC analysis	ND	ND	61-230 (128)‡	ND	ND	ND
0.126 m ² and 0.49 m ² chambers§/GC analysis	149-824 (355)‡	13-414 (160)‡	29-337 (177)‡	24-488 (205)‡	21-406 (142)‡	22-528 (218)‡
0.0079 m ² chambers in 49x49 m grid/GC analysis	(191)‡	74-854 (292)‡*	ND	ND	ND	ND

ND, not determined.

*44-64 during the afternoon and 20-70 under inversion conditions.

†Single integrated value and uncertainty range from -10 to +30% of value.

‡Range and mean.

§Ungrazed area only.

Open Chambers

Open chambers are coupled to the atmosphere via an air inlet through which outside air is continuously drawn into the chamber and forced to flow over the enclosed soil surface. The gas flux from the soil is calculated from concentration difference, flow rate, and area covered by the chamber (IAEA, 1992). The main advantages of open compared to closed chambers are:

- effects of N_2O accumulation are reduced or eliminated. This permits longer periods of measurements
- conditions outside and inside the chamber can be more similar than for closed chambers.

However, open types are sensitive to pressure deficits inside the chamber caused by the induced air flow which may cause artificially high fluxes. N_2O concentrations are lower than in closed chambers, thus the method is less sensitive.

2.12.2 Micrometeorological Methods

The basic concept of micrometeorological approaches, described in Denmead (1983), is that gas transport is accomplished by the eddying motion of the atmosphere which displaces parcels of air from one level to another. Three different approaches are used: eddy correlation, flux gradient and mass balance:

- eddy correlation technique is obtained by correlating the instantaneous vertical wind speed at a point with the instantaneous concentration of that gas. In the natural environment the eddies which are important in the transport process occur with frequencies extending up to 5 to 10 Hz. Therefore a rapid response detector is required;
- flux gradient theory is based on the concept of diffusion of the gas along its mean concentration gradient. The method requires measurement of mean gas concentrations at a number of heights above the surface and knowledge of the appropriate diffusion coefficients;
- in mass balance method, gas flux density is related to the horizontal distance from the upwind edge of the field and the top of the air layer influenced by the emission of the gas. The method assumes that the mean horizontal turbulent flux is much smaller than the mean, horizontal advective flux. The top of the air layer influenced by the emission of the gas is a function of stability and surface roughness but can generally be simply estimated.

The advantages of the micrometeorological methods are that they do not disturb the environmental or soil processes which influence gas exchange; they allow continuous rapid measurement, thus facilitating the investigation of environmental effects; and they provide a measure of the average flux over a large area, thereby minimising the sampling problem created by point to point variation.

However, compared to soil cover method micrometeorological techniques could be used only during periods of high N_2O flux, because only then were the differences in N_2O concentrations between sampling heights greater than the minimum detectable difference of the analytical method (Mosier and Hutchinson, 1981).

Other disadvantages are the need for large uniform fields with a minimum of air turbulence and appropriate weather conditions as periods of turbulence can give erroneous results (Granli and Bockman, 1994).

2.12.3 Ultra-large Chambers with Long-path IR Spectrometers

The ultra-large chambers, described in IAEA (1992), is a new promising technique but not yet ready for routine flux measurements. Infra-red absorption spectrometers are now available which can give an average value for the concentration over distances of tens or hundreds of meters. These instruments are potentially very useful for measurements of average emissions from a whole experimental plot, by covering the plot temporarily with a large canopy, to act as a chamber and retain N_2O emitted from the soil. Such a procedure also has the advantage, compared with the flux-gradient method and other micrometeorological methods mentioned above, of not requiring the associated measurements of windspeed etc., and of allowing the comparison of emissions from different treatments in a replicated field experiment, without any interference being caused by emissions from adjacent plots. Two such systems are available: a Fourier Transform Infra Red (FTIR) spectrometer with a mirror system which allows multiple reflections, and thus a total path of up to 1 km, that is capable of measuring N_2O concentration changes down to a fraction of 1 ppb; and simpler, less sensitive IR spectrometer (the Siemens-Plessey 'Hawk' system), with the capacity to detect a concentration change of ca. 25 ppb of N_2O (IAEA, 1992).

2.12.4 Nitrous Oxide Emissions Variability

A problem in measuring N_2O emissions from soils is the large spatial and diurnal variations. In some cases the variation is considerable within only few metres on the same experimental plot. There are number of studies which report high spatial variation and also there is seasonal variation.

Seasonal Variation

Most studies report that seasonal pattern of N_2O emissions occur during winter time, which is not surprising due to soil moisture factor which tends to be higher in winter. For example, Kessavalou et al. (1998b) had 3 to 47% of nitrous emissions accounted for winter fluxes. Kaiser et al. (1998) reported 50% of annual N_2O emissions during winter (October to February) in Northern hemisphere, which resulted from both physical release of subsurface-produced N_2O during soil freezing and microbial N_2O production during daily thawing and freezing cycles. Moreover, the authors stated that the total N_2O losses during the winter increased with decreasing dry matter-to-N-content ratio of the plant residues incorporated into the soil by ploughing. This suggests that plant species can influence N_2O emissions.

While thawing of the soil surface dictates timing, N availability strongly governs the magnitude of the N_2O emissions (Lemke et al., 1998a). The authors reported 16 to 60% N_2O emissions occurred during and just following snow melt in the spring. These mentioned above emissions were related to wet season.

Spatial Variation

Magnitude of N_2O emissions is highly variable due to complex interactions between controlling factors, and high coefficient of variations are often reported. Even within the sampling boundary N_2O fluxes can differ significantly. For instance, Lemke et al. (1998b) reported large-scale variability of up to 92% which the authors related to differences in clay content. Factors such as topsoil nitrate, ammonium, and water contents and air permeability may contribute to the variability of N_2O emissions (Ball et al., 1997). However, sometimes variations are hard to explain without detailed sampling and measurements.

Unfortunately, often reported coefficients of variation range from 8% to 325% (Mahmood et al., 1998) to up to 6001% (Teira-Esmatges et al., 1998) are common in these kinds of studies. The spatial variability of denitrification could be attributed to “hot-spots” associated with high local concentrations of organic matter. The formation of these hot spots was governed by the creation of anaerobic conditions due to increased respiration, following the introduction of a source of decomposable organic matter to the soil microbes (Christensen and Tiedje, 1988).

2.13 Summary

This literature review has shown that N_2O contribution to the global greenhouse gases is small but significant. Its contribution in New Zealand context is four times of that elsewhere. Detrimental impact of N_2O in the environment is mainly trapping of outgoing terrestrial radiation and its involvement in destruction of stratospheric ozone.

N_2O is known to result mainly from soil denitrification and nitrification processes. Although N_2O is usually by-product of these processes magnitude of its release depends on several controlling factors and complex interactions between them. Emissions of N_2O are best explained by soil moisture content, temperature, organic matter, nitrate level, physical properties and pH. However, they are not always correlated with those factors due to complexity of soil micro-organisms responsible for soil chemical processes.

Measurement methods for N_2O fluxes have evolved from simple chamber technique to micrometeorological and infra-red spectrometer methods capable of estimates from larger area fields. Despite new techniques N_2O emissions are still characterised with high spatial as well as temporal variations making inventory assessments less confident.

Despite such inherent variations in spatial variability it is important to provide a degree of quantification of these measurements. Hence, this study was undertaken to understand the likely quantifiable impacts of soils cropped with tillage, no-tillage and compare this with pasture soils N_2O emissions.

Chapter 3

Materials and Methods

3.1 Experimental sites

Two field sites were chosen for this study, based on their suitability for comparison. The primary site Kairanga (40° 21’ S, 175° 39’ E) and the second site at Massey University (latitude 40° 23’ S, 175° 38’ E) were within the Manawatu region of the North Island of New Zealand. The summary of rainfall and soil temperatures for both sites is given in Table 3.1. The cooperating farmers used management typical practices and the presence of our instrumentation in the fields did not interfere with the practices.

Table 3.1: Summary of monthly climatological observations data taken at 09.00 hrs at AgResearch and Aorangi Research stations close to study sites.

	AgResearch				Aorangi		
1998-99	Mean Rainfall (mm)	Air Temperature (°C)		Soil Temperature (°C)	Mean Rainfall (mm)	Soil Temperature (°C)	
Months		min	max			min	max
November					86.0	16.4	19.0
December	46.5	12.3	20.8	17.4	36.4	18.0	20.7
January	39.4	14.9	25.0	21.0	56.2	20.2	23.4
February	20.1	13.1	24.9	20.2	43.6	19.2	22.3
March	34.3	14.3	23.9	18.6	45.4	18.6	20.6
April	65.3	10.1	19.3	13.7	77.8	15.2	16.8
May	114.6	7.6	16.9	10.9	136.0	12.8	14.5
June	67.9	4.9	14.2	8.1	102.0	10.6	17.1
July	94.5	4.9	13.5	7.8	107.0	n/a	n/a
August	86.5	3.4	13.4	6.5	58.0	n/a	n/a
September	49.6	6.0	15.8	9.9	62.8	11.5	12.8

3.1.1 Kairanga Site

These prime experimental sites are located about 10 km northwest of Palmerston North. The soil has been classified as Kairanga silt loam with very poor drainage (Table 3.2) and soil characteristics described in Saggar et al. (2000).

Table 3.2: Selected soil characteristics of the fields at the Kairanga site.

Sites	Soil classification		Grid reference	pH	Organic C	Total N	Microbial C
	NZ	US		1:2.5 soil:water	(%)	(%)	mg/kg soil
Permanent Pasture (PP)	Typic Orthic Gley	Typic Endoaquept	NZMS 260 S24 272 609	5.65±0.01*	4.99±0.32	0.47±0.09	1585±5
17 years cultivated (K17)	Typic Orthic Gley	Typic Endoaquept	NZMS 260 S24 272 609	5.58±0.04	3.30±0.49	0.28±0.05	474±11
34 years cultivated (K34)	Typic Orthic Gley	Typic Endoaquept	NZMS 260 S24 272 609	6.20±0.02	2.03±0.30	0.18±0.09	261±15

* Values represent mean±standard error

These farms representing a permanent pasture (PP), 17 years conventional cultivation (K17) and 34 years conventional cultivation (K34) grown maize (*Zea mays*) crop (Figure 3.1) were included in this study. Permanent pasture (Figure 3.2) was used as a control and had 160 cows strip-grazed on 3 acre (1.21 ha) sections of the farm for 9 hours during the day and 12 hours over the night.

Maize was sown at both cultivated farms in late October 1998. The 34 years farm received 306.5 kg/ha of (15:10:10:8) fertilizer at sowing and additional 300 kg/ha of urea as side dressing applied in early December 1998. Maize crop harvested for silage produced 16 t dry matter/ha.

The K17 plot received 153 kg/ha (half of K34) of 15:10:10:8 starter fertiliser applied end of October and 300 kg/ha of urea side-dressed in early December 1998. The yield of maize grain was 6.9 t/ha.



Figure 3.1 Kairanga site 34 years (K34) treatment field.



Figure 3.2 Permanent pasture (PP) field treatment at Kairanga site.

The crop growth season was dry. Coupled with the very dry summer (which followed a very wet October), the fertilizer added and especially the urea side-dressing would not have been utilized effectively, because of the lack of rainfall and very dry soils. Urea pellets were still visible two weeks after application.

3.1.2 Massey Site

Massey experiment plots were established by the previous Department of Agricultural Engineering (now the Institute of Technology and Engineering) at Massey University Turitea campus, Palmerston North in 1995 (Figure 3.3) (Choudhary et al., 1996). The soil has been classified as Ohakea silt loam (Typic endoaqualf) and Gleyic Luvisol (FAO), with weakly clay-illuvial pseudomadenti-pallic representing youngest yellow-grey earth with poor natural drainage. The experimental design involved:

- Conventional Tillage (CT) - permanent pasture land was converted to a double crop rotation using conventional practices. Plots were moldboard ploughed and followed by rolling and two passes of a power harrow for seedbed preparation.
- No-Tillage (NT) - similarly, permanent pasture land was converted to a double crop rotation using no-tillage practice. There was no prior cultivation and weeds were controlled by using Roundup (360 g/l glyphosate) at 4 l/ha. Sowing was done by direct drilling.
- Permanent Pasture (PP) - was used as a control. Together with other treatment plots they were rotationally sheep grazed. Plots consisted of high fertility grass species including ryegrass (*Lolium perenne*), yorkshire fog (*Holcus lantus*), poa (*Poa spp*) and cocksfoot (*Dactylis glomerata*) represented 65% of sward, white clover (*Trifolium repens*) and other legumes ~20% (suckling clover (*T. dubium* Sibth), subterranean clover (*T. Subterraneum*) and lotus (*Lotus spp*)). Few weed species including catsea (*Hypochaeris radicata*), hawkbit (*Leontodon taraxacoides* (villars) Merat), ribgrass (*Plantago lanceolata*), and chickweed (*Cerastium glomeratum* Thuill) constituted the remaining 15% of the pasture community (Aslam et al., 1999).



Figure 3.3 Massey site experimental treatment plots.

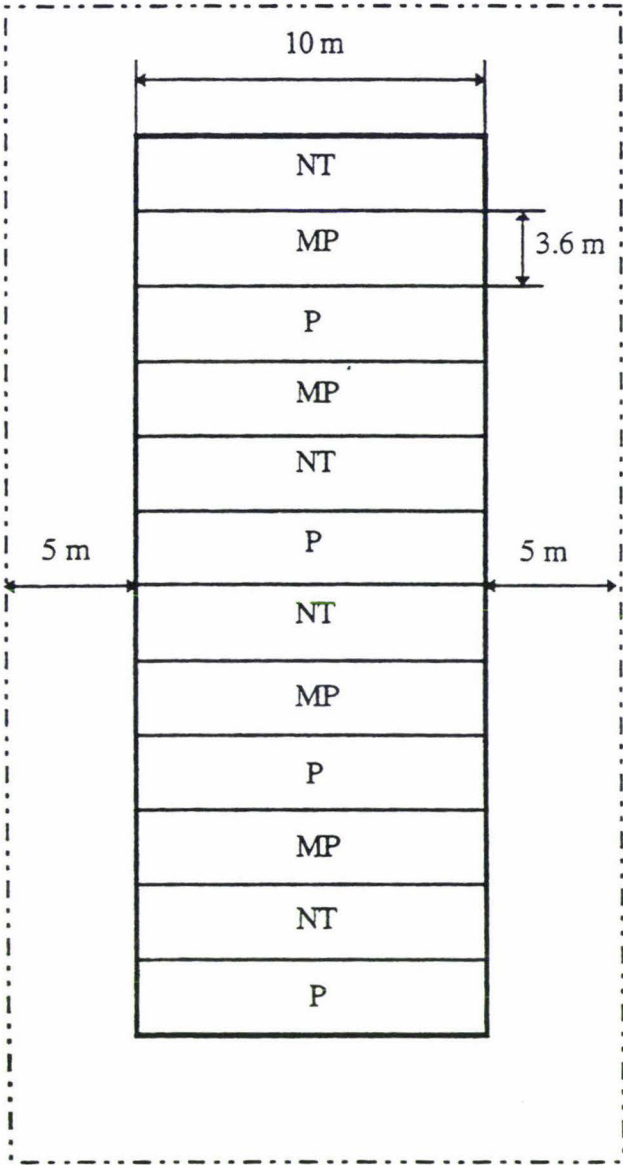


Figure 3.4 Schematic layout of experimental treatment design plots at Massey site.

CT - conventional tillage; NT - no-tillage; PP - permanent pasture

Each treatment had four replicates arranged in a randomized block design. Each plot was 17 m long and 3.6 m wide with a 5 meter headland for machinery operation on both sides of the field (Figure 3.4).

Summer fodder maize was sown on the 8th of December 1998 at seed rate of 65 kg/ha. Aitchison seed drill (Seedmatic 1112) was used for sowing and simultaneous Nitrophoska (12% N, 10% P, 10% K, 1% S) fertilizer was applied at the rate of 120 kg/ha. The maize was then grazed by a mob of sheep at maturity.

The winter oats were sown at a seed rate of 120 kg ha⁻¹ on 19 April 1999 with 200 kg/ha of Nitrophoska fertilizer with the Aitchison seed drill (Seedmatic 1112). The crop at maturity was later sheep grazed.

3.2 Measurement of Field N₂O Emission

Nitrous oxide measurement techniques available nowadays include small to medium chambers, ultra-large chambers with IR spectrometer, micrometeorological method and soil air analysis. All the methods are widely used, however, in most of the studies N₂O fluxes from soil and plant systems are measured using chamber methods involving gas chromatography analysis of N₂O (Mosier and Hutchinsom, 1981; Ryden and Rolston, 1983; Goodroad et al., 1984; Smith et al., 1994; Carran et al., 1995; Kaiser et al., 1998).

Micrometeorological methods can measure gas emissions from the fields without disturbing the gas exchange between the atmosphere and the soil/crop system. However, the usefulness of these method is limited by requirements such as: expensive equipment, extensive uniform surface areas with constant atmospheric conditions during each measurement period. In addition to those requirements small concentration fluxes are difficult to measure with micrometeorological methods.

Few requirements of micrometeorological methods can be overcome by another promising technique such as ultra-large chamber with IR spectrometer which can measure N₂O emissions from large areas and do not require uniformity of the fields and associated measurements of wind speed. The technique is limited to gas concentration measurements until the methodology for making the necessary accompanying

measurements to estimate gas flux is perfected (Mosier, 1990).

Small to medium size chambers are more suitable for comparing N₂O emissions from treatments on a typical small plots as at Massey site. Other obvious advantages of this method are:

- easy handling and randomization of chamber position over the duration of an experiment, as opposed to the use of fixed sampling positions
- no interference with agricultural operations such as tillage particularly at farming sites used
- low ratio rates of N₂O fluxes can be measured
- no extra equipment requiring electrical supply is needed
- the chambers are simple and relatively inexpensive to construct

Nitrous oxide flux measurements were made periodically each month at both sites for a year using closed chamber technique developed by Mosier and Hutchinson (1981) with slight modifications. Attempts were made to coordinate measurements at certain intervals, however, because of instrumental and logistics problems, constraints on time, and occasionally unsuitable weather conditions sampling times varied during experiment. Additional fortnightly measurements were also carried out.

IAEA (1992) recommends to use at least four chambers if the coefficient of variation is less than 100%, and at least 20 replicates for each treatment if CV is above 100%. Mosier and Hutchinson (1981) estimated N₂O flux density by micrometeorological method, and it always fell within the range of the four individual flux estimates made by the soil cover method. The authors interpreted this agreement as evidence that four soil cover determinations adequately sampled soil variability in N₂O emissions. In this study due to the extent of the project and funds available only four chambers were employed for each treatment.

3.2.1 Procedure

Nitrous oxide flux measurement procedure involved the following:

1. Installation of chambers

2. *Applying high vacuum grease and closing the lid*
3. *Use syringe to take gas sample through the air vent fitted on the lid cover (both, syringe and air vent, fitted with three way tap)*
4. *Repeat step 3 after 1, 2 and 3 hours from first gas sampling*
5. *Transport gas samples to the laboratory for analysis by electron capture detector (ECD-GC)*
6. *Calculate N_2O flux from the concentration increase*

The sampling chamber consisted of two cylinders glued together (Figure 3.5). Main outer custom made cylinder was 0.1 m tall and have been designed to be closed with the lid. Cylinder and the lid were molded from PVC material and were 6 mm thick. The lid was designed to be screwed on the top of the cylinder.

In order to make the chamber longer cylindrical pipe was glued to the inner part of the custom made cylinder. Inner cylinder was a 0.2 m tall polypropylene pipe of diameter 0.24 m. The bottom end of the chamber was machine-beveled to facilitate its insertion into the ground.

Chambers were inserted into the soil depth of 0.1 m giving a head space volume of 4.6 l on enclosure with a plastic lid (Figure 3.5). An area covered by chambers was 45 cm². To assure that there was no leakage beneath the lid cover high vacuum grease was applied onto rubber band used as a seal. Chambers were removed after measurements until the next sampling.

Quadruplicate measurements were made at approximately same locations within a small uniform area of the field on each sampling date at Kairanga site and chambers at Massey site were placed along the treatment plots. Chambers in cropped fields at Kairanga were placed between maize rows. At Massey, due to cropping for grazing, distance between rows did not allow placement of chamber in the interrow. However, plant interference during chamber installments were kept to a minimum.

Adequate precautions were taken to minimize disturbance of the energy and mass transfer processes normally operating at and above the soil surface. For example, temperature raise tends to enhance soil nitrous oxide flux. To avoid temperature changes

in the soil and atmosphere under the chamber, during sampling on sunny day, the chambers were covered with insulating material and basket over it.

Initially the chambers were left for three hours with an hour interval for air sampling in order to detect if there was any leakage. Gas samples were taken from the headspace immediately after sealing (t_0) and at 1 hour time intervals thereafter over a period of 3 hours. This was done to check the linearity of concentration increase in the chamber.

Since after several sampling occasions N_2O concentration tended to have linear increase over three hour period, in later samplings it was reduced to only two hours.

Head space gas samples were collected through the air vent on the lid cover using 60 ml polypropylene syringes fitted with 3-way taps (Figure 3.6). Syringes with gas samples were held in the plastic bags in set of four and were kept in air conditioned laboratory with constant temperature for overnight. Because of concern over the permeability of polypropylene to N_2O , field samples were analyzed as soon as possible after collection, usually within 24 hours. Ambient air at t_0 , collected at the time of chamber installation, was used as a reference for calculating N_2O gas fluxes.

Nitrous oxide flux was computed from the concentration increase over the time. The following formula was used for calculation:

$$N_2O - N \text{ flux} = \frac{\left[\left(\frac{28.0134}{22.4} \times \frac{273}{273 + t^{\circ}C} \right) \times V \times \frac{T_1 - T_0}{1000} \times \frac{1}{1(2;3)} \right]}{\text{Area}} \quad (\mu\text{g } N_2O\text{-N/m}^2/\text{h})$$

where:

28.0134 and 22.4 - are constants;

$t^{\circ}C$ – soil temperature at 10 cm depth;

V – chamber volume (L);

$T_1 - T_0$ - is the change in ppb measured;

T_1 – N_2O measured after one hour interval;

T_0 – N_2O measured at the time of closing lid (ambient concentration);

A – area covered by the chamber (m^2);

$1/1(2;3)$ - is 1/incubation time in hours, i.e. 1 (or 2 or 3) hour buildup



Figure 3.5 Closed cover chamber used to collect field nitrous oxide (N₂O) emissions.

3.2.2 Analysis of N₂O Concentration

Analyses were done using Mosier and Mack (1980) method capable of precise determination of ambient N₂O concentrations. Air samples were analyzed for N₂O using a GC. Hewlett-Packard 3385A integrator recorded the sample chromatogram and performed peak area integration. Argon-methane carrier gas consisting methane (10±0.3%), oxygen (<10 ppm), water (<5 ppm) in argon was used in the columns.

Gas samples from syringes were introduced into a 5 cm³ gas sampling loop through an inlet system shown in Figure 3.7. Each analysis took approximately 6 minutes and 10 samples per hour could be routinely analyzed.

To calibrate and check for possible contamination of the sampling system, routine tests were made by running analysis of standard preparation. Standard gas was prepared with concentration of 914 ppb.

Standard Preparation

To prepare standard gas 1.067 litre jar was used. First the jar was flashed with pure nitrogen for about 20 seconds and then filled with nitrogen gas. A 50 ml sample of filled nitrogen gas from the jar was taken out and replaced with a 50 ml of standard gas (20 ppm N₂O in nitrogen (19.2±0.4 ppm N₂O)) to give a final concentration of 914 ppb.

3.3 Pilot Experiments

3.3.1 Exploratory Sampling

Initially a pilot study was undertaken to measure N₂O flux using the chamber technique. Exploratory sampling was conducted on November 3, 1998 after maize planting. A field with a history having 34 years of continuous cultivation with maize/barley was chosen for this purpose. Three chambers were installed in the morning. Four gas samples were taken from each chamber, first at the time of closing the lid, and after 1, 2 and 3 hours. Due to the time constraints only one sample could be analysed next day on November 4. The rest of gas samples were analysed on November 5.

3.3.2 Spatial Variability

Due to high spatial variability reported by other studies of N₂O emissions (Carran et al., 1995; Ruz-Jerez et al., 1994) twelve chambers per treatment at Massey site were used to determine spatial variability.

3.3.3 N₂O Emissions During Seedbed Preparation

Nitrous oxide emissions were measured during seedbed preparation in March. Chambers were installed in the CT plots at Massey site within few days after ploughing. Fluxes were compared to the emissions measured next day immediately after power harrowing operation.

3.3.4 Prolonged Continuous Measurement

Concurrently, in March to examine effect of prolonged continuous measurement on N₂O flux gas samples were collected over the longer time than usual 2-3 hours. Chambers were installed in all treatment plots at Massey site and were left in the soil for 9 hours with periodic sampling at 0, 1, 2, 3, 5, 7, and 9 hours.

3.4 Ancillary Measurements

3.4.1 Soil Moisture

Soil moisture at 10 cm depth was measured each time during N₂O measurements. Field samples were collected, weighed, oven-dried to constant mass at 105°C and then weighed again. The final mass M_s , and the difference between the wet and dry masses M_w were used to calculate gravimetric soil water content (SMC):

$$SMC = \frac{M_w}{M_s} \times 100\%$$

3.4.2 Soil Temperature

Soil temperature at 10 cm depth was measured at each nitrous oxide sampling time at each site using handheld digital thermometer. Temperature probe used for this purpose was inserted into the soil next to each chamber. Temperature indications were recorded manually.

3.4.3 Soil pH, Total C and N

Soil pH, total carbon and nitrogen, and bulk density were measured once. Soil organic carbon content was measured using a Laboratory Equipment Corporation (Leco) high-frequency induction furnace (Blakemore et al., 1987). The measurements were done on 0.5 subsamples taken from air-dried soil collected from each plot. Samples were collected from two depths, 0-10 and 10-20 cm, from each plot after the winter oats being grazed, and from the adjacent pasture plots on September 1999. Soil from each plot was bulked before subsampling. Organic-N content of the 0-10 and 10-20 cm samples were determined by the Kjeldahl method.

3.4.4 Rainfall Data

Rainfall data were obtained for both sites from nearby stations. AgResearch (E05363) rainfall data was used for Massey site as it was located around Turitea campus. For Kairanga fields data from Aorangi Research Station on Lockwood road was obtained.

3.4.5 Statistical Analysis

An exploratory analyses of the data was performed to determine the distribution of N_2O emission rates. The results of the first step indicated whether or not the data needed to be transformed in order to satisfy the normal distribution assumption of the ANOVA analyses. Log-transformation was satisfactory for the majority of sampling dates.

A general linear model procedure (GLM) was used for analyses of experimental data. An analyses of variance (ANOVA) using test of least significant difference (LSD) at 5% confidence level was used for comparisons of treatments. Regression analyses between measured soil moisture and N_2O emission rates were completed using data analysis option of Excel.

All the raw data collected during the period of study is appended in appendices I to II.



Figure 3.6 Installed chamber fitted with 3-way tap for withdrawing air samples using syringe.



Figure 3.7 Injecting 10 ml of gas sample into gas chromatography (GC) instrument to measure nitrous oxide (N_2O) concentration.

Chapter 4

Results and Discussion

4.1 Overview

Nitrous oxide emissions measured with closed chamber technique in this study are believed to have wide soil variability (Mosier and Hutchinson, 1981). During field sampling all precautions were taken to minimise possible leakage or disturbance to processes occurring at and above soil surface. However, few problems arose during field samplings especially during dry and hot summer period of measurements. Forced insertion of chambers into the soil was rather difficult in dry soil despite the bottom of the chambers being sharp. IAEA (1992) guidelines have recommended that the chamber should only minimally affect the surface boundary layer resistance. In these samplings, however, it is unknown what effect direct forcing of chambers caused.

The problems associated with the in-situ removable closed chambers technique for measuring N_2O fluxes have been discussed previously by Mosier (1990) and IAEA (1992). In this study, one major problem with the chambers employed rather than the methodology was evident. As the chambers were forced into the soil, it led to cracks and occasionally breakage of chambers itself. However, there were sufficient chambers to obtain four replicates from each treatment.

It is worth noting that Kessavalou (1998b) recorded more N_2O from the cropped row than inter row locations. The authors reported mean N_2O flux from the row 0.5 to 2.7 times greater than that from the interrow zone, probably due to more available C and subsequently greater nitrification and denitrification activities in the vicinity of plant roots where the fertiliser N was placed. This study did not encompass the measurements from the interrow, therefore emissions from the management systems assessed may have underestimated actual N_2O fluxes.

4.2 Pilot Experiment

4.2.1 Exploratory Sampling

Results obtained from a preliminary study on calibration of the chamber technique and assessment of field variability in N₂O emissions are shown in Table 4.1 N₂O emissions varied widely among the replicates. Replicate 1 gave over 4 times as much N₂O as replicate 2 during the first hour. The low rate of N₂O emission in replicate 2 may partly be due to some leakage. The soil at the time of this study was dry and the insertion of chambers probably did not allow tight seal between the chamber and the field soil.

Table 4.1: N₂O emission rates using the exploratory samples in the pilot experiment

Replicates	Hourly increase (µg N ₂ O-N/ha/hr)		
R ₁	22	16	10
R ₂	5	2	2
R ₃	14	12	10

The results (Table 4.1) also show that the rate of N₂O emission in all the replicates declined over time. This rate of decline in N₂O emissions among the three chambers was not consistent. Because of these variations it was decided to employ a minimum of four chambers for future regular measurements.

The other variable was the timing of analysis after collection of the samples. Results of samples collected from a chamber which were analysed next day showed marked difference as compared with the analysis of gas samples from the same chamber after two days. Values of N₂O two days after collection were 11 to 36% lower than those analysed one day after following collection with a mean decrease of about 29% (Table 4.2). Williams et al. (1999) also detected N₂O losses from the syringes of about 10% after 24 hours and about 40% after 3 days. These results indicate that syringes used were perhaps not suitable to store gas samples for long periods and suggest that gas samples be analysed as soon as possible and certainly not exceeding 24 hours after collection.

Table 4.2: Effect of time of analysis on N₂O emissions following collection of gas samples from the field.

Time following gas sample collection	N ₂ O flux µg N ₂ O-N/ha/hr			
	1 st hour	2 nd hour	3 rd hour	Mean
Sampling day 0				
Analysis on day 1	34	18	15	22
Analysis on day 2	22	16	10	16
Decrease in N ₂ O emission (%)	35	11	36	29

4.2.2 Spatial Variation

Among others, Carran et al. (1995) have also measured large variability in the N₂O emissions in the field because of soil heterogeneity. To confirm such potential baseline variations in the data within the treatments, a total of 12 samples were taken representing one sample from each treatment at the Massey site. The data (Table 4.3) showed large inherent variations in N₂O fluxes (with CV values between 110-127% across all treatments), which reflected natural soil heterogeneity, and perhaps the measurement technique used rather than the real differences due to the tillage and cropping systems evaluated. Similar variations in the PP, CT and NT suggests processes occurring in these treatments are the same.

Table 4.3: N₂O emissions from 12 chambers measured to determine baseline variation

Treatment	R ₁	R ₂	R ₃	R ₄	R ₅	R ₆	R ₇	R ₈	R ₉	R ₁₀	R ₁₁	R ₁₂	Mean	CV (%)
PP	190	56	60	290	18	26	69	28	329	28	10	15	93	120
CT	36	38	92	68	103	91	171	65	421	231	664	70	172	110
NT	142	976	72	173	202	61	59	547	125	163	40	38	216	127

PP = permanent pasture; CT = conventional tillage system; NT = no tillage system

4.2.3 Pilot Experiment on Effect of Seedbed Preparation on N₂O Emission

An earlier study by Kessavalou et al. (1998a) showed that to accurately estimate annual net greenhouse gas fluxes for an agro-ecosystem, gas flux determinations must also be made at critical times near tillage and wetting events in addition to monitoring fluxes under normal field conditions.

A pilot experiment was conducted to assess the immediate effect of soil disturbance on N₂O fluxes during land preparation in March, after grazing fodder maize. N₂O fluxes were first measured within a few days after ploughing (March 17) and subsequent measurements were taken on March 18, immediately after power harrowing. Soil gravimetric moisture content at the 0-10 cm depth was obtained in close proximity to the chambers.

Table 4.4: Comparison of N₂O fluxes before (March 17) and after (March 18) power harrowing in the CT treatment at the Massey site.

Replicates	March 17	March 18
	g N ₂ O-N/ha/hr	
R ₁	0.72	0.28
R ₂	0.76	0.26
R ₃	0.44	0.30
R ₄	0.65	0.13
Mean ± stdev	0.64 ± 0.14	0.24 ± 0.08

The data (Table 4.4) obtained from these measurements showed significant differences between two sampling occasions. N₂O fluxes measured on March 17, after moldboard ploughing but before power harrowing, were 0.64 ± 0.14 g N₂O-N/ha/hr. Fluxes immediately after power harrowing were 0.24 ± 0.08 g N₂O-N/ha/hr. Comparison of two events showed that N₂O fluxes declined by over 65% within first hour after power harrowing. Similar observation was recorded by Kessavalou et al. (1998a) during summer period, when N₂O emissions declined by about 64% within 30 minutes following disking. These authors also noted that, although in their experiment N₂O emissions returned to the pre-disking level 8 hours after disking, but declined again and remained low for the rest of the study period. The authors related this phenomena to low water filled pore space (WFPS) conditions in the top 7.6 cm of soil.

In the present study, N₂O emission rate returned to the pre-power harrowing levels one month after power-harrowing (April 22 in Table 4.8) which most likely was associated with increased soil moisture content. Although the rate of N₂O fluxes increased in April (ranging from 0.29 to 2.04) the mean values 0.76 g N₂O-N/ha/hr did not differ much.

This clearly supports the view that soil loosening with ploughing and secondary cultivation increases aeration, enhances moisture evaporation and subsequently reduces denitrification rate.

4.2.4 Effect of Prolonged Measurements on N₂O Flux

To examine the effect of prolonged measurements on N₂O flux a replicated experiment was undertaken. Measurements were made continuously for 9 hours, with periodic gas sampling after 0, 1, 2, 3, 5, 7, and 9 hours for PP, NT and CT tillage treatments at the Massey site. The results from these measurements are presented in Figure 4.1.

In all treatments, N₂O concentrations in the chamber increased with time. Apart from few sampling events, there was a linear increase in N₂O concentration with time in all the treatments but the slope of the regression line was below 1.0. A departure from the straight line observed in some replicates appears to be probably due to an inadequately sealed chamber or due to changes in the N₂O diffusion rate. According to the IAEA (1992) report the decrease in N₂O concentration gradient between zone of production in the soil and the chamber atmosphere with time changes the N₂O diffusion rate. As the chambers were air-tight, the most likely reason of decreased rate of N₂O accumulation inside the chamber appeared to be a slow diffusion rate with time.

In general, the results indicated that prolonged incubation of chambers is not recommended due to an adverse effects of incubation on N₂O production. However, few samples per chamber should be allowed to monitor the chamber performance.

4.3 Massey Experimental Site

4.3.1 Effects of Tillage on Soil pH, Total C and N

The results of soil analysis including pH, total C and N are presented in Table 4.5. Attention is drawn to the fact that, inadvertently, analysis were done on oven-dried soil samples. It is usually recommended that the samples should be air-dried, since oven drying cause changes in several chemical properties of soil. However, this oversight should not effect total C and N results.

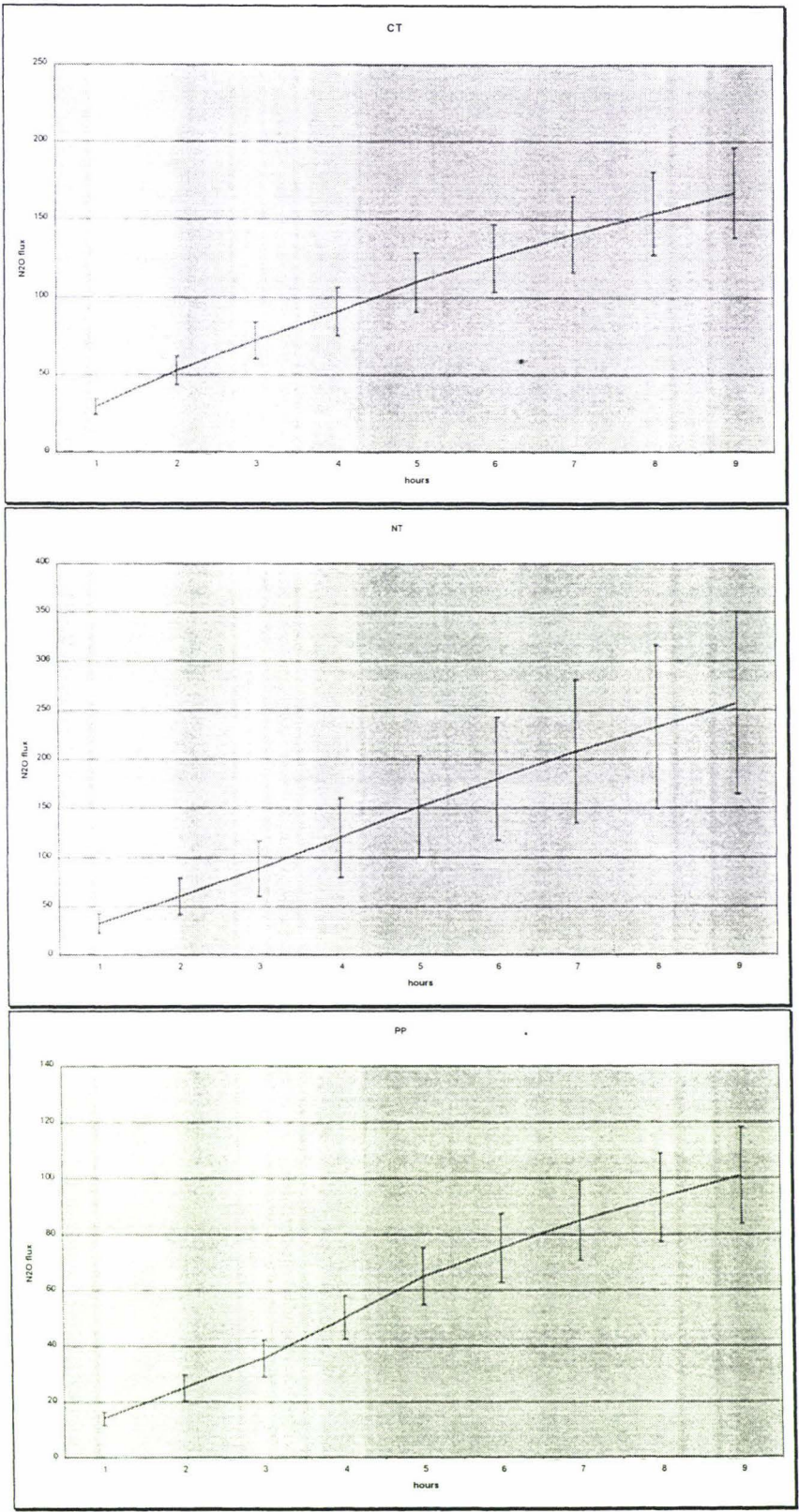


Figure 4.1 Increase in N₂O concentration in a closed chamber over time in the treatments: (a) conventional tillage (CT); (b) no-tillage (NT); (c) permanent pasture (PP). (bars represent standard error)

Table 4.5: Ohakea silt loam soil pH, total C and total N of the Massey experimental site.

Characteristic	PP	CT	NT
0 – 10 cm depth			
Total C (%)	2.75 a	2.17 c	2.43 b
Total N (%)	0.24 a	0.20 b	0.22 a b
pH (H₂O)	5.31 a	5.30 a	5.10 b
10 - 20 cm depth			
Total C (%)	1.84 a	1.93 a	1.80 a
Total N (%)	0.17 a	0.18 a	0.17 a
pH (H₂O)	5.32 a	5.26 a	5.10 b

*Values followed with the same letter in the row show no significant difference ($p < 0.05$)
PP = permanent pasture; CT = conventional tillage system; NT = no tillage system*

4.3.1.1 *Effect of Tillage Techniques on Soil pH*

Soil pH at both depths, 0-10 cm and 10-20 cm, in the PP and CT treatments showed no differences. The soil showed moderate acidity with an average pH of 5.3, which is common in New Zealand soils. However, pH in the NT treatment was significantly lower compared to the PP and CT treatments at both soil depths (Table 4.5).

The results suggest that adoption of long-term NT tended to decrease soil pH following conversion of pasture to cropping. This further confirms the findings of Choudhary et al. (1997) that in continuously cropped soils using no-tillage method over many years, surface soil becomes acidic possibly due to stratification with surface applied fertilisers. However, other results from these plots within first and second year of cropping indicated no change in soil pH (Guo, 1997; Aslam, 1998).

4.3.1.2 *Effect of Tillage Techniques on Total C*

Plots under double cropping showed marked decline in total organic C compared to the levels in soil under PP. The changes in total C were most pronounced in the 0-10 cm depth (Table 4.5) where 4 years of continuous cropping resulted in an overall decline in C of 12% in the NT and 21% in the CT treatments.

At 0-20 cm soil depth, total C was lower than in upper 10 cm of soil and distributed reasonably evenly in all plots. Similar results of losses of total C from native soils and long-term pastures following cropping have been widely reported (Sparling et al., 1992; Saggar et al., 1998, 2000; Aslam et al., 2000; Shepherd et al., 2000).

The higher amount of total C (11%) in the NT compared to the CT treatment was possibly due to high retention of crop residue over the soil surface, less soil disturbance and subsequently less erosion. These results confirm similar observations by Aslam (1998) who reported that total C was 19% higher in the NT soils compared to that in the CT soil.

Sparling et al. (1992) and Saggar et al. (1998, 2000) have attributed the decline in the C content of the Manawatu soils to decreased C input under arable farming compared with pasture, and enhanced mineralization of organic C caused by cultivation.

4.3.1.3 Effect of Tillage Technique on Total N

Total N at the 0-10 cm depth was 0.24, 0.20 and 0.22% in the PP, CT and NT treatments respectively (Table 4.5). Comparison of treatments showed a significant decline in total N content in the CT compared to the PP treatment, but no discernible differences were detected in the NT compared to the PP and CT treatment. Similar results were reported by Aslam (1998) where total N content in the CT was significantly lower than the PP and NT treatment.

At 10-20 cm depth, total N was lower than in upper 10 cm, however, similar to C it was more evenly distributed in all treatments (Table 4.5).

4.3.2 Tillage Effect on Field N₂O Emissions

In order to assess the effect of tillage treatments on soil N₂O emissions, monthly (and occasionally fortnightly) measurements were taken during cropped as well as fallow periods over one year cycle. The measurements at the Massey site started on December 22, 1998 and continued until September 8, 1999. During this period a total of 10 measurements were completed. No N₂O measurements were undertaken in May because of unavailability of the chambers.

The mean, minimum and maximum N₂O emissions from the NT, CT and PP plots are presented in Table 4.6. The mean daily and yearly emission rates are calculated and shown in Table 4.7.

Table 4.6: The effects of tillage systems on the ranges of N₂O emissions from Massey plots.

Treatment	Min	Max
	g N ₂ O-N/ha/hr	
PP	0.01	0.69
CT	0.03	6.84
NT	0.04	7.41

The lowest and the highest fluxes were 0.01 and 7.41 g N₂O-N/ha/hr, respectively. Although soils can sometimes act as a sink (Mahmood et al., 1998; Teira-Esmatges et al., 1998) there was no evidence of negative N₂O fluxes in the chambers. Initial statistical analysis using raw data showed non-normality of error distribution and comparison of treatment means did not seem to show real differences (Table 4.8). Due to these reasons comparison of treatments had to be done using log-transformed data. The N₂O emission rates were approximately log-normally distributed. Log-normally distributed N₂O emission rates have also been reported by Ambus and Christensen (1994). The results from the logarithmic transformed data are shown in Table 4.9.

Table 4.7: The effects of tillage systems on the means of N₂O emissions from Massey plots.

Treatment	N ₂ O emissions (Means)		
	Per Hour	Per Day	Per Year
	g N ₂ O-N/ha		kg N ₂ O-N/ha
PP	0.19 b	5.00	1.66
CT	1.05 a	25.00	9.20
NT	1.37 a	33.00	12.00

Values with the same letter in the column are not significantly different (*p*<0.05)
PP = permanent pasture; CT = conventional tillage system; NT = no tillage system

Further interpretations of the results here are based on log transformed analysis of data. This computation highlighted differences in some samples whereas initial analysis were indicating no differences. Examples are N_2O fluxes measured on January 7 and August 19 when initial statistical analysis showed no significant differences. Even the treatment mean values varied by several orders.

Results showed that on most sampling dates the NT and CT treatments had significantly higher N_2O fluxes compared to the PP. The April measurement showed no such difference among the treatments, which appeared to be mainly associated with high variability among the replicates in each treatment.

The N_2O fluxes data in March showed similar trend to that in April. Differences in emission values were again not different, although the measured data (Table 4.8) showed that emissions in the PP were less than one fifth to one half to those for the CT and NT values, respectively. This again points to high replicate variability in the N_2O emission values as discussed in section 4.3.3.2.

N_2O emissions during the fodder maize growth period (January to March) were generally low. Starting from December when fluxes were high, with the PP, CT and NT treatments at 0.19, 2.46 and 1.51 g N_2O -N/ha/hr respectively. N_2O emissions declined considerably culminating in the lowest emissions in all treatments in February with the PP, CT and NT at 0.01, 0.07 and 0.09 g N_2O -N/ha/hr respectively.

It is worth noting that the December N_2O emissions were several fold larger than those measured during summer. Similar phenomenon was recorded by Carran et al. (1995) who attributed it to relatively large pool of both NH_4 and NO_3 in the soil.

This sharp decline coincided, firstly, with low soil moisture content which had dropped by more than half compared to December soil moisture content (Table 4.10). This corresponded with rainfall in February which was only 20.1 mm for the month. Secondly, lowest emissions also coincided with high temperatures during summer (Figure 4.2) which is one of the controlling factors of denitrification. Nevertheless, N_2O fluxes from the CT and NT plots always remained higher than those from the PP plots.

Table 4.8: Effects of tillage systems on the monthly means of N₂O emissions data at Massey site (December 1998 to September 1999).

Treatment	Field N ₂ O emissions (µg N ₂ O-N/m ² /hr)									
	22 Dec	7 Jan	29 Jan	11 Feb	18 Mar	22 Apr	16 Jun	28 Jul	19 Aug	8 Sep
PP	19 b	7 a	3 b	1 b	12 b	29 a	31 b	34 b	10 a	43 b
CT	246 a	27 a	14 a	7 a	64 a	76 a	189 a b	118 b	219 a	133 a b
NT	151 ab	28 a	21 a	9 a	30 b	34 a	244 a	507 a	187 a	163 a
LSD _{0.05}	172	23	9	5	22	65	162	188	311	107

Values followed by the same letter in the column show no significant difference ($p < 0.05$)
PP = permanent pasture; CT = conventional tillage system; NT = no tillage system

Table 4.9: Effects of tillage systems on the monthly means of log transformed N₂O emissions at Massey site (December 1998 to September 1999).

	Field N ₂ O emissions									
Treatment	22 Dec	7 Jan	29 Jan	11 Feb	18 Mar	22 Apr	16 Jun	28 Jul	19 Aug	8 Sep
PP	2.84 b	1.86 b	0.90 b	0.00 b	2.42 c	2.92 a	3.35 b	3.51 b	2.17 b	3.57 b
CT	5.43 a	3.09 a	2.52 a	1.82 a	4.14 a	4.11 a	5.06 a	4.44 b	4.61 a	4.76 a
NT	4.69 a	3.26 a	2.99 a	2.06 a	3.26 b	3.37 a	5.35 a	6.18 a	5.03 a	5.04 a
LSD _{0.05}	1.05	0.78	0.64	0.69	0.71	1.41	1.01	0.97	1.55	0.99

Values followed by the same letter in the column show no significant difference ($p<0.05$)
PP = permanent pasture; CT = conventional tillage system; NT = no tillage system

From February onward, N₂O emission rates started to gradually increase until March. A few days after tillage, gas emissions from the CT enhanced significantly compared to the NT and PP plots. Although N₂O flux in the CT was 54% and 81% higher than that in NT and PP, respectively, a day earlier, it declined sharply after seedbed preparation with power harrow as discussed in section 4.2.3. These results showed some insight into the effects on N₂O efflux of recently cultivated soil as earlier suggested by Kessavalou (1998a).

The results obtained following this tillage operation and during oats crop establishment in April showed relatively, although insignificantly, higher N₂O flux from the CT (55% and 62%) as compared to the NT and PP plots, respectively. These data confirms that cultivated soil allows higher or similar N₂O emissions to the NT soil during autumn season. Spring fluxes from CT were also found to be higher by MacKenzie et al. (1998).

The N₂O emissions data (Table 4.8) from June to September (during winter and spring period) generally reflected increased microbial activity irrespective of tillage or cropping system as reported by Aslam et al. (1999). The N₂O emissions during this period were consistently high reaching up to 6.84, 7.41 and 0.69 g N₂O-N/ha/hr in the CT, NT and PP treatments, respectively. The PP, however, continued to emit lower amounts of N₂O gas as compared to the NT and CT treatments even with the increased soil moisture content. Similar results were reported for CO₂ emission rates from these treatments (Aslam et al., 2000).

These findings support earlier suggestions by a number of researchers (Kaiser et al., 1998; Lemke et al., 1998a; McKenzie et al., 1998) who postulated that N₂O emissions were significantly affected by climate. The New Zealand winter is marked by, not unexpectedly, low soil temperature and high rainfall. This resulted in increased soil moisture content. Despite low temperature, high soil moisture increased N₂O emissions significantly predictably due to denitrification. However, low soil temperature probably also accounted for higher N₂O portion from denitrification (Keeney et al., 1979).

Because N₂O is a product of both nitrification and denitrification processes, nitrification was presumably the major source of summer N₂O flux, as soil moisture content during this period decreased and allowed predominantly aerobic soil conditions (Figure 4.2).

Conversely, extremely high N_2O fluxes during winter time indicated that denitrification was the major source of N_2O emissions from these soils.

4.3.3 Summary

Overall, when comparing the means of data gathered throughout the ten month period, N_2O fluxes were substantially higher in the NT and CT compared to the PP treatment. This indicates that conversion of pasture land to cropping significantly increases N_2O emissions. Similarly, untilled soils without pasture cover also enhanced N_2O gas emissions. The results confirm earlier investigations by Kessavalou et al. (1998b) and Mosier et al. (1997) who reported 25-50% higher N_2O emissions from the croplands within three years of conversion from native grassland.

The possible reason of rather low N_2O emissions from the PP could be nitrogen utilisation by the growing grasses, whereas in the CT and NT plots the roots distribution is not as dense as proliferation of grass roots. Recent studies by Kessavalou et al. (1998b) showed that considerably less nitrification occurred in grassland soils than in cropped soils, allowing less opportunity for denitrification in grassland soils.

In this study, overall there were no differences in the N_2O emission rates between the CT and NT treatments. These results are in accordance with that of Kessavalou et al. (1998b). Other studies such as Aulakh et al. (1984) have reported higher annual emission rates from NT soil compared to cultivated soils. There were some sampling occasions when the NT had relatively, although insignificantly, higher fluxes than the CT in this study. It is possible that 4 years of continuous cropping with NT is not sufficient time to allow pronounced differences to develop between these two tillage methods.

4.3.3.1 *Effect of Soil Moisture on N_2O Emissions*

There are number of other reported research studies on soil moisture effect on N_2O fluxes (Sitaula and Bakken, 1993; Mosier et al., 1981; Bouwman, 1990). To determine if a possible relationship existed between N_2O fluxes and gravimetric soil moisture content at 0-10 cm depth, moisture measurements were made from close proximity to the installed chambers at the same time as gas emission sampling was taken.

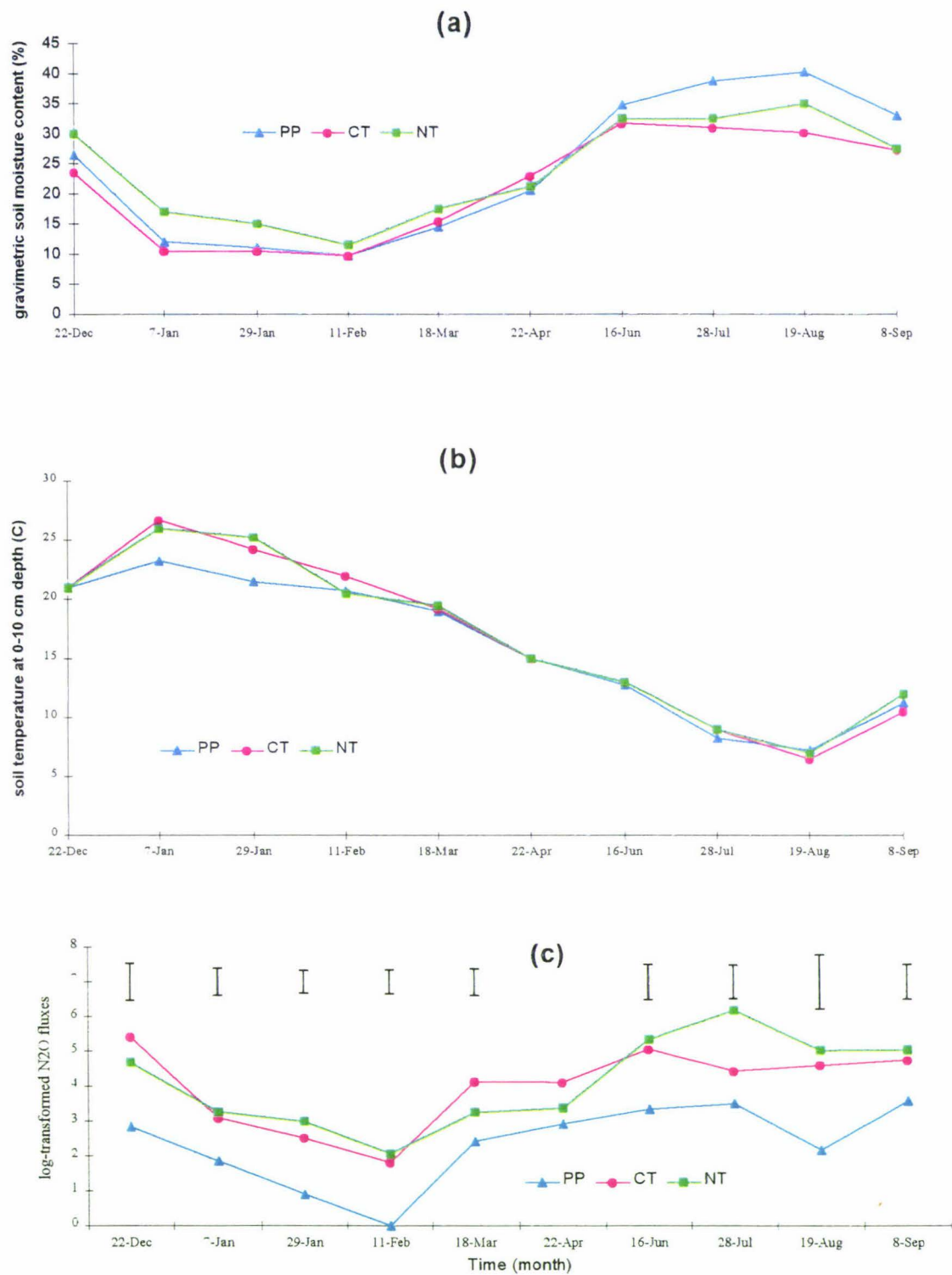


Figure 4.2 The effect of tillage treatment of the PP, CT and NT on the monthly data of soil moisture (a), temperature (b) and log-transformed means of N₂O emissions (c).

Table 4.10 presents results of moisture content in all treatments throughout the period. Values represent means of four replicates. Regression analyses and correlation of moisture content with N_2O fluxes were computed using all four replicates since they were measured separately for each chamber.

Tillage practices generally influenced water content in all treatments during different months of the year. The NT plots had higher moisture content compared to the CT and PP plots during summer and early autumn when rainfall events were not frequent. Choudhary (1979) suggested that direct drilling enhances soil moisture retention. Lower moisture content in the PP could be due to high transpiration rate from the growing pasture. However, during winter period soil moisture in the PP was generally higher compared to the NT and CT plots. This could be associated with generally less evapotranspiration unlike during summer time.

Generally, soil moisture content appeared to govern N_2O emission rates. The lowest fluxes occurred when soil water content was low and tended to increase with higher moisture content (Figure 4.2). As described elsewhere there were low N_2O emissions during dry summer period and consistently high fluxes during winter. A number of regression analyses to obtain better fit equation between the soil moisture content and monthly N_2O fluxes were computed.

A linear regression model using the soil moisture and measured N_2O emissions data gave a weak correlation (Figure 4.3). To examine these relationship further transformations were computed to observe if any relationship existed between the values of N_2O fluxes and soil moisture.

Overall, the log-transformed N_2O data showed better correlation with field soil moisture with the PP ($r=0.73$), CT ($r=0.75$) and NT ($r=0.86$) (Figure 4.4). This indicated that soil moisture content and N_2O emissions had strong relationship in all treatments. Nevertheless, it is clear that a large number of samples were required to fully explain the relationship between the soil moisture and N_2O emission rates. These relationships indicated that field soil moisture content generally, although partially, determined the N_2O emissions.

Other factors such as soil temperature also played a role in the amount of N₂O release. These data imply that in the Manawatu region of New Zealand, the onset of rainy period is a major factor triggering N₂O emissions.

Table 4.10: Effect of tillage techniques on soil moisture content at 0-10 cm depth during N₂O emission measurements

Treat	Gravimetric soil moisture content (%)									
	22-Dec	7-Jan	29-Jan	11-Feb	18-Mar	22-Apr	16-Jun	28-Jul	19-Aug	8-Sep
PP	27 b	12 b	11 b	10 b	15 b	21 b	35 a	39 a	40 a	33 a
CT	24 c	11 c	11 b	10 b	16 b	23 a	32 b	31 b	30 c	27 b
NT	30 a	17 a	15 a	12 a	18 a	21 ab	33 ab	33 b	35 b	28 b
LSD _{0.05}	0.75	1.19	0.53	1.36	1.19	2.37	2.29	2.49	2.80	1.98

Values followed by the same letter in the column show no significant difference ($p < 0.05$)
PP = permanent pasture; CT = conventional tillage system; NT = no tillage system

4.3.3.2 Seasonal Variation

Regardless of cropping and tillage management used, general seasonal patterns at this site are well defined, although one-year data was not enough to statistically build time series. Low N₂O emission values were predominant during dry season while wet season values were considerably higher (Figure 4.2). This trend was similar across all tillage treatments.

Seasonal grouping of N₂O data when log-transformed showed significant differences in the N₂O emissions in all three treatments (Table 4.11). Because there was only one measurement conducted in the first week of September, spring season was not included in the comparison. Seasonal variation in N₂O emission from the PP was in the order of winter=autumn>summer. Although fluxes in the CT were higher in winter than in the autumn season, there were no differences between the summer and autumn data. Similar to pasture, in the NT treatment the seasonal variations in N₂O emission were in the order of winter>autumn=summer.

The seasonal variations indicated that N₂O emissions were generally higher during winter period as compared to summer and autumn. This could be triggered by wet weather which was more frequent and intense generally starting from the end of autumn

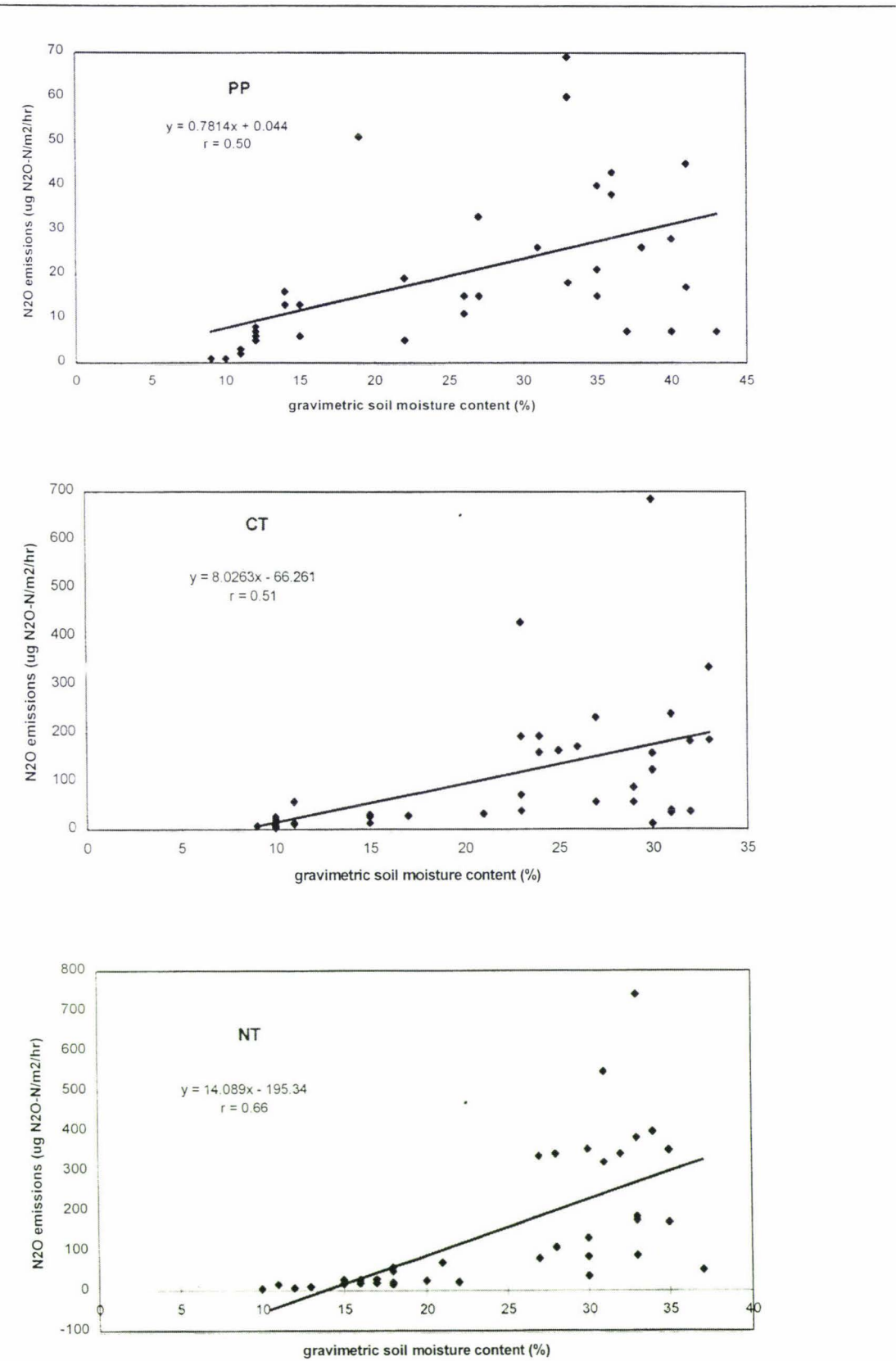


Figure 4.3 Regression analysis between measured soil moisture content and N₂O emissions in the PP (permanent pasture), CT (conventional tillage) and NT (no-tillage) treatments.

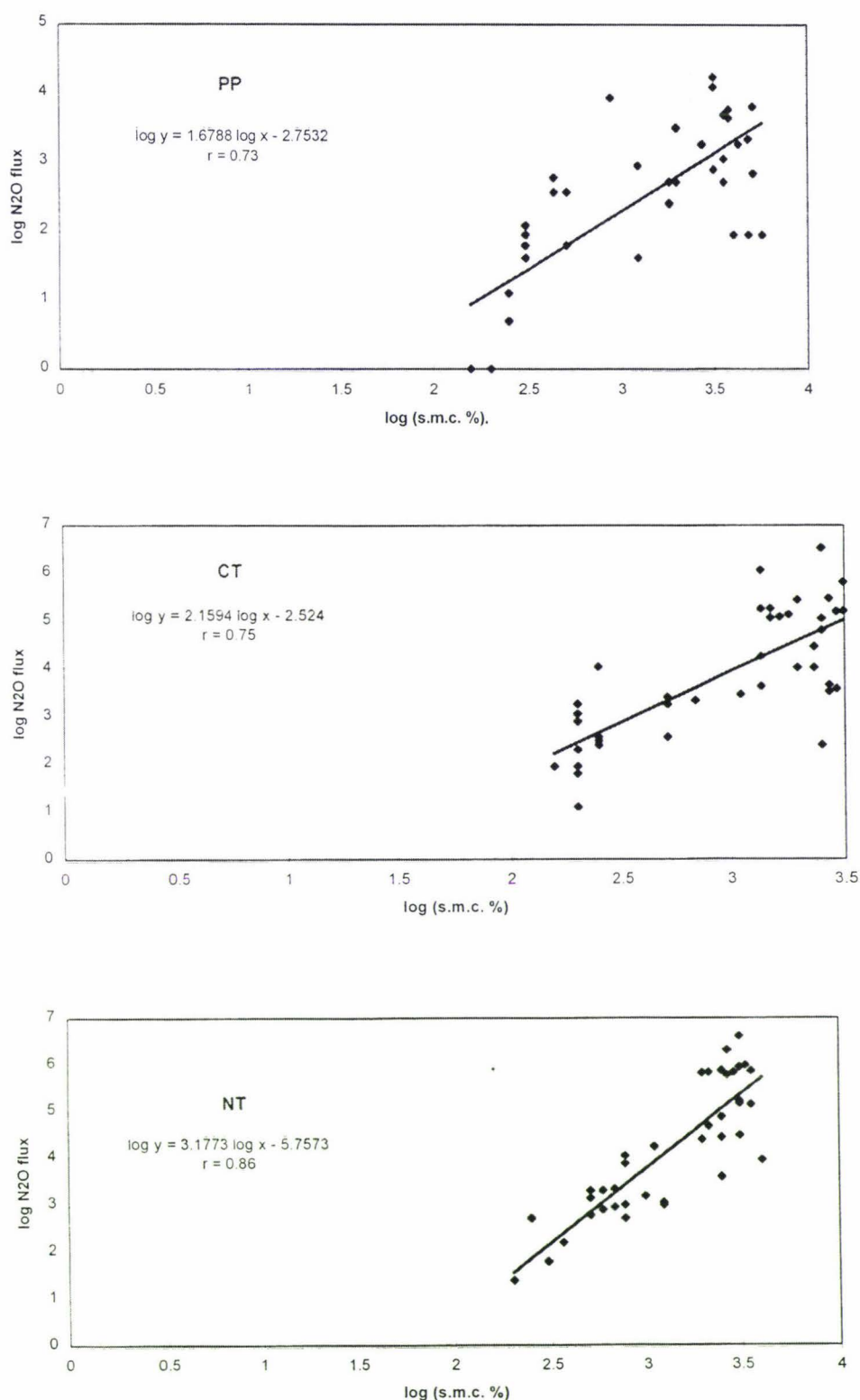


Figure 4.4 Regression analysis of log-transformed data between soil moisture content and N₂O emissions in the PP (permanent pasture), CT (conventional tillage) and NT (no-tillage) treatments. (s.m.c. - soil moisture content)

Table 4.11: Seasonal field N₂O emissions as affected by the PP, CT and NT treatments.

Treatment	Field N ₂ O emissions			
	Summer (December-January-February)	Autumn (March-April-May)	Winter (June-July-August)	LSD _{0.05}
PP	1.94 b	2.86 a	3.19 a	0.71
CT	4.25 ab	3.77 b	4.91 a	1.04
NT	3.77 b	3.34 b	5.71 a	0.84

*Values with the same letter in the row are not significantly different (p<0.05)
PP = permanent pasture; CT = conventional tillage system; NT = no tillage system*

and continuing during winter time, thus creating favourable conditions for denitrification.

The data also show large seasonal as well as monthly variation in N₂O emissions. Some of this variability was presumably caused by soil moisture and temperature. For example, N₂O fluxes during first sampling on December 22 were several orders higher than the next sampling on January 7. This suggested that high soil temperature coupled with the major rainfall event in December gave bursts of N₂O fluxes. Kessavalou et al. (1998a) also reported up to 5-fold increase in N₂O emissions following wetting. These authors had postulated that failure to include these short-lived episodic gas pulses in annual flux estimations may underestimate annual N₂O loss of up to 24%.

It is worth noting that when considering the last three year rainfall events data (Figure 4.5) during measurement period, it showed a clear uneven distribution in rainfall. This may have had an effect on time of release and the flux magnitude of N₂O . Kaiser et al. (1998) found approximately 50% of the annual losses during winter period from October to February in the northern hemisphere. This highlights the importance of this period for the assessment of total N₂O losses from arable lands in the temperate climate of New Zealand.

4.3.3.3 Spatial Variation

During N₂O emission measurements, there were marked spatial variations in all treatments. Cumulative coefficient of variation (CV) of treatments ranged from 39 to

140% . This was not unexpected as other researchers such as Lemke et al. (1998b) have reported up to 92% of the large-scale spatial variability, which the authors related to the differences in soil clay content in that experimental site. Others reported more than two times higher spatial variations in N_2O data (Mahmood et al., 1998; Teira-Esmatges et al., 1998).

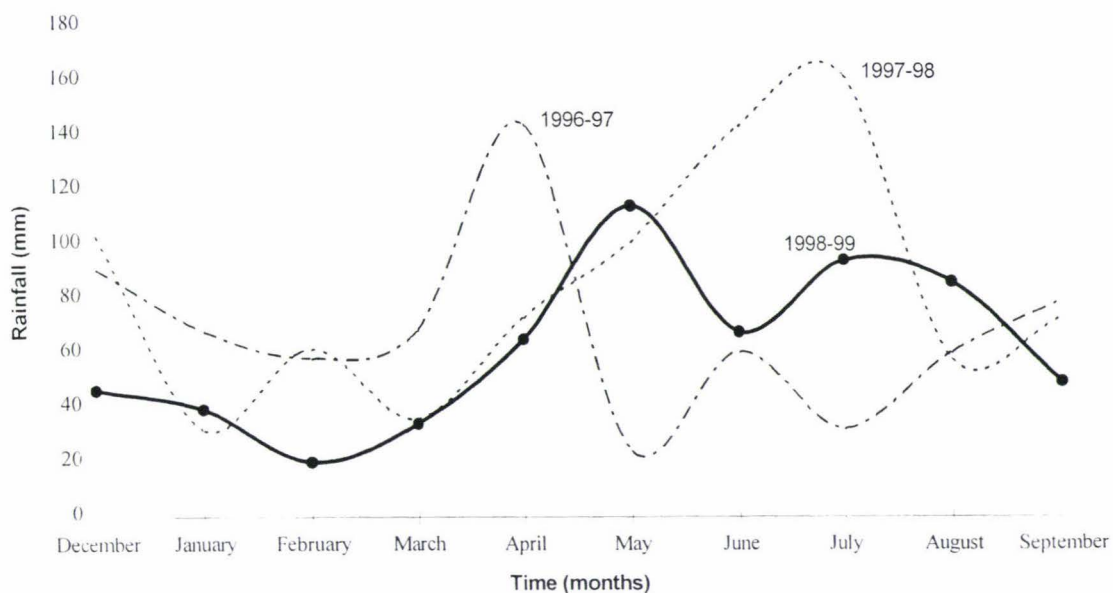


Figure 4.5 Monthly rainfall data for the Massey site from December 1998 to September 1999 and 1996-97, 1997-98.

Clayton et al. (1994) noted that N_2O emissions arising from denitrification tend to be more spatially variable than those arising from the aerobic process of nitrification. Incubations of soil with acetylene suggested that large N_2O fluxes at the Kairanga field site can also result in high denitrification potential (Brian Daly, *pers. comm.*).

The spatial variability in denitrification could be attributed to “hot-spots” associated with high local concentrations of organic matter, nitrate level and soil condition. As Christensen and Tiedje (1988) have observed, the formation of these hot spots was governed by the creation of anaerobic conditions due to increased respiration, following the introduction of a source of decomposable organic matter to the soil microbes. Similar observations were reported by Clemens et al. (1999).

Randomly selected sampling positions within the field could further contribute to high variability in N_2O fluxes. On some occasions N_2O fluxes ranged almost 10-fold with the lowest and highest recorded within the same treatment. As the plots were at approximately 4° slope, the lower end of the field tended to have more biological activity since fluxes from this end were generally approximately 2 times greater than from the upper end of the field.

Although the pilot experiment on spatial variation (described in section 4.2.2) showed large variation (CV=119%) the range of coefficients of variation of four replicates taken throughout measurement period in PP (CV=40%) and NT (CV=56%) were always below 100%. The N_2O values in the NT and CT generally had higher spatial variation compared to pasture.

4.3.4 Summary

The results obtained from the Massey site indicate that tillage practices have a significant effect on N_2O emissions. In general context, the present study suggests that the annual fluxes as low as 0.09, 0.26 and 0.35 kg N_2O -N/ha could be expected from the PP, CT and NT management systems receiving fertiliser application in the North Island. Annual fluxes of as high as 6, 60 and 65 kg N_2O -N/ha would also likely to occur in situations when soils are predisposed to give high bursts of emissions. N_2O emissions from cropped fields were substantially higher than those from the PP which, not unexpectedly, reflect reduced total N and C contents in these soils. However, there were no marked differences between CT and NT treatments.

Strong correlation between N_2O emissions and soil water content in all treatments suggests that the high rainfall and wet winter and early springs together with soil properties such as drainage characteristics are important in assessment of N_2O fluxes from these fields. Therefore, mitigation practices to reduce N_2O emissions should be directed towards the periods of high emissions.

4.4 Kairanga Experimental Site

4.4.1 Effects of Tillage on Soil pH, Total C and N

Sampling of these sites for soil chemical analysis was undertaken in a separate study on soil organic matter, microbial biomass, and soil structure and reported Saggar et al. (1998, 2000). The results are presented in Table 3.2.

4.4.2 Tillage Effect on Field N₂O Emissions

N₂O emissions from the Kairanga site included cropped as well as winter fallow period. Measurements started in November 1998 and continued until September 1999. During this period a total of 14 measurements were made. However, the samples collected on March 31 could not be analysed due to instrument malfunction.

The ranges of N₂O emissions representing a mean of four replicates from the 17 (K17) and 34 (K34) years of continuous maize growing fields, and permanent pasture (PP) are shown in Table 4.12. The lowest and the highest fluxes at these sites were 0.01 and 3.43 g N₂O-N/ha/hr, respectively. Initial analysis of data (Table 4.14) did not show normal distribution and comparison of treatments were done using log-transformed values (Table 4.15).

Table 4.12: The effects of tillage systems on the ranges of N₂O emissions from Kairanga plots.

Treatment	Min	Max
	g N ₂ O-N/ha/hr	
PP	0.02	1.52
K17	0.02	1.93
K34	0.01	3.43

PP = permanent pasture; K17 (K34) = 17 years (34 years) of conventional continuously grown maize

The estimated annual N₂O emissions from the PP, K17 and K34 (calculated as the mean of all individual closed cover chamber measurements between November 1998 and September 1999) were similar at 3.24, 3.42 and 2.37 kg N₂O-N/ha/year, respectively. Mean emission rates for the PP were within the range reported by Carran et al. (1995) from the similar grazed sites on Kairanga soil. The N₂O emissions from the K17 and

K34 fields are comparable with that recorded by Jacinthe and Dick (1997) for similar continuous corn system in Ohio (USA) 3.7 kg N₂O-N/ha/year. There were also large variations in N₂O emissions during the year with the mean flux rates ranging from 0.175 to 13.32, 0.175 to 16.91 and 0.088 to 30.05 kg N₂O-N/ha/year in PP, K17 and K34, respectively (calculated from Table 4.12).

Table 4.13: The effects of tillage systems on the means of N₂O emissions from Kairanga plots.

Treatment	N ₂ O emissions		
	Per Hour	Per Day	Per Year
	g N ₂ O-N/ha		kg N ₂ O-N/ha
PP	0.37	9.00	3.24
K17	0.39	9.00	3.42
K34	0.27	7.00	2.37
LSD _{0.05}	ns	ns	ns

PP = permanent pasture; K17 (K34) = 17 years (34 years) of conventional continuously grown maize

Generally, there were pronounced differences between treatments at each sampling, however, higher emissions of one treatment were not always consistent. Only measurements on December 16 and June 23 showed no difference between means of all treatments which were associated with high variability (CV= 81 and 143%) of data obtained that day.

Although overall comparison of treatment means did not show any discernible differences between management practices, there were signs that the K34 had lower emissions compared to the PP. Fluctuations in N₂O fluxes throughout the sampling period could be the possible reason for this.

During early crop growth period (November and December), the management practices had little effect on N₂O emissions. During the first eight weeks of measurements, N₂O fluxes from the K17 treatment were lower than in the K34 field which probably resulted from half rate (153 kg/ha) of the starter N fertiliser applied to the K17 field at sowing. Additional side-dressing of 300 kg/ha of urea in early December did not appear to have much effect on N₂O emissions. Coupled with the very dry summer (which followed a

Table 4.14: Effects of length of continuous cropping and permanent pasture on the mean monthly N₂O emissions
at the Kairanga site (November 1998 to September 1999).

Treatment	Field N ₂ O emissions (µg N ₂ O-N/ha/hr)												
	12 Nov	16 Dec	5 Jan	26 Jan	9 Feb	15 Mar	19 Apr	19 May	23 May	23 Jun	26 Jul	17 Aug	1 Sep
PP	41 a	39 a	8 b	4 c	5 c	99 a	21 a	22 a	13 a	26 a	68 a	57 b	77 a
K17	7 b	16 a	16 b	57 a	21 b	33 b	6 b	6 b	5 b	62 a	92 a	135 a	49 a
K34	25 ab	24 a	38 a	31 b	60 a	18 b	9 b	3 b	4 b	113 a	10 b	10 b	4 b
LSD _{0.05}	31	34	15	17	13	45	6	6	4	153	56	55	30

Values followed by the same letter in the column show no significant differences (p<0.05)
PP = permanent pasture; K17 = 17 years of conventional continuously grown maize; K34 = 34 years of conventional continuously grown maize

Table 4.15: **Effect of length of continuous cropping and permanent pasture on the mean of log-transformed**
monthly N₂O emissions at Kairanga site (November 1998 to September 1999).

	Field N ₂ O emissions												
Treatment	12 Nov	16 Dec	5 Jan	26 Jan	9 Feb	15 Mar	19 Apr	19 May	23 May	23 Jun	26 Jul	17 Aug	1 Sep
PP	3.38 a	3.40 a	1.90 c	1.27 c	1.66 c	4.53 a	3.02 a	3.06 a	2.51 a	3.24 a	4.19 a	4.01 b	4.31 a
K17	1.94 b	2.72 a	2.74 b	4.02 a	2.92 b	3.28 b	1.78 c	1.52 b	1.64 b	3.72 a	4.39 a	4.83 a	3.81 a
K34	3.20 a	3.02 a	3.57 a	3.38 b	4.07 a	2.84 b	2.19 b	1.14 b	1.28 b	4.10 a	2.29 b	2.30 c	1.10 b
LSD _{0.05}	0.98	1.01	0.77	0.53	0.56	0.84	0.33	0.74	0.60	1.51	0.63	0.57	1.03

Values followed by the same letter in the column show no significant differences (p<0.05)
PP = permanent pasture; K17 = 17 years of conventional continuously grown maize; K34 = 34 years of conventional continuously grown maize

very wet October), the fertiliser added and especially the urea side-dressing would not have been utilised effectively because of lack of rainfall and resulting dry soils as suggested by T. G. Shepherd (*pers. comm.*). Some urea granules were still visible on the soil surface two weeks after application.

In January, the effects of management practices started to show up when N_2O emissions in the PP had dramatically fallen reaching the lowest flux (approximately 1 g N_2O -N/ha/day) during the whole sampling period due to rapid drying of soil in December-February summer period. On the other hand, N_2O fluxes remained high in the K17 and K34 fields indicating that during maize growth period in summer, the biological activities were at a peak.

In February, N_2O emissions started to decrease in the K17 but arose in the PP field. Similarly, in the K34 field, N_2O fluxes started to drop sharply in March. February and March were also low in rainfall (Figure 4.9). However, 8.5 mm rain prior to sampling on March 15 and 9.5 mm during the day seemed to have created a burst of N_2O flux from permanent pasture. It reached the highest emission rate of almost 24 g N_2O -N/ha/day recorded during the sampling period.

The steady decrease of N_2O emissions in the K17 and K34 fields coincided with crop maturation. The decrease was more pronounced in the K34 after harvest. Maize in the K34 field was harvested on March 17 and 18 for silage with yield of 16.1 t/ha DM due to the poor crop that year. Maize in the K17 resembled to that in the K34 field and was in senescent condition during autumn.

Although denitrification measured by using acetylene inhibition at the same sites indicated that denitrification rates could be high (Daly, *pers. comm.*). More frequent rainfall events did not seem to effect N_2O emissions in the K17 and K34 fields which were the lowest during April and May months. N_2O emissions decreased after March, but the PP maintained higher fluxes compared with cropped fields. There are several explanations to this phenomena. It can be related to low precipitation which was not enough to raise soil moisture, thus creating likely anaerobic condition for denitrification. Alternatively, crop depleted soil nitrate levels, bare soil, low moisture conditions and

senescent crop perhaps slowed down biological activities in the soil resulting in reduced N_2O emissions.

Maize in the K17 was harvested with grain yield of 6.9 t/ha prior to N_2O emissions sampling on May 19 with crop residue left on soil surface. On May 19, sampling was conducted two days after a rainfall event (30 mm) but the expected higher N_2O fluxes did not occur. To determine if the N_2O fluxes were affected after four days, another sampling was carried on May 23. The results showed no such difference between two sampling days in the K17 and K34. This may be due to the unchanged soil conditions although soil temperature in the K17 decreased moderately. Soil moisture in the K17 did not differ much due to the surface residue left in the field. However, slight decrease in soil moisture in the PP led to 41% reduction in N_2O fluxes. This indicates that soil moisture was a governing factor in N_2O emissions.

Results obtained during fallow period in June following low N_2O emissions during and after-harvest showed a sudden 10-fold increase in N_2O emissions both in the K17 and K34 fields. A more steady increase was observed in the PP. However, as the weather progressed into more colder period, significant differences became apparent between the treatments. N_2O fluxes declined and returned to the similar rates observed during autumn in the K34, whereas the PP and K17 field emissions continued with a steady increase. Overall, N_2O emissions in the PP and K17 remained high during wet period.

The explanation of such behaviour of soil N_2O fluxes are rather complicated without procuring additional measurements of soil parameters. Based on the limited available data, low emissions during winter were expected due to low temperatures as measured in the K34 field. On the other hand, interestingly the highest fluxes measured were during winter, and were 27 and 22 g N_2O -N/ha/day in the K34 and K17 respectively. These high flux rates were generally found under wet conditions thus probably reflecting the occurrence of an enhanced denitrification process.

Effect of higher organic matter content plus surface residue in the K17 field could also be related to the hypothesis that microbial N_2O production during winter is limited by available C as suggested by Kaiser et al. (1998). These authors observed a significant

relationship between total N₂O emissions during winter and the dry matter-to-N content ratio of the incorporated plant residues.

Contrarily, the K34 had low soil organic matter content and, as the maize crop was harvested for silage, this left little surface residue input. When considering the N₂O emission rates after harvest in March, and if one off event of high burst of N₂O emissions in June was discarded, it can be hypothesized that soil nitrate level, which was low in the K34 field, and applied fertiliser has already been utilised by the maize, was the possible determining factor in governing the emissions. Moreover, given the favourable moisture conditions and the winter fallow fluxes reported to be higher (Kessavalou et al., 1998b), the K34 N₂O fluxes were still low. This further indicates that soil nitrate level was probably the limiting factor in this case. Further elaboration could possibly be made. However, these must be supported by more extensive sampling of other controlling factors.

Higher N₂O fluxes in the PP could be associated with pastoral management system used. The PP used in this study was intensively grazed by dairy stock. The influence of grazing animals on input of readily decomposable excretal N has already been stressed by Ruz-Jerez et al. (1994) and Williams et al. (1999). Considering that urine is a concentrated N solution (approx. 10 g N/litre of which 80-90% is urea) and the effective rate of application within urine patches is often greater than the equivalent of 500 kg N/ha (Haynes and Sherlock, 1986), denitrification losses could be as high as 30 to 40% as suggested by Carran et al. (1982). High N inputs in the form of urine were apparently beyond the ability of plant uptake.

4.4.2.1 Effect of Soil Moisture on N₂O Emissions

Results of gravimetric soil moisture measurements from the vicinity of the installed chambers are summarised in Table 4.16. The values represent means of four measurements.

Soil moisture content (SMC) was significantly affected by the tillage treatments throughout the year. The K34 field SMC was always 22 to 52% lower compared to the K17 field. The pattern of soil moisture changes in the K17 closely resembled the K34

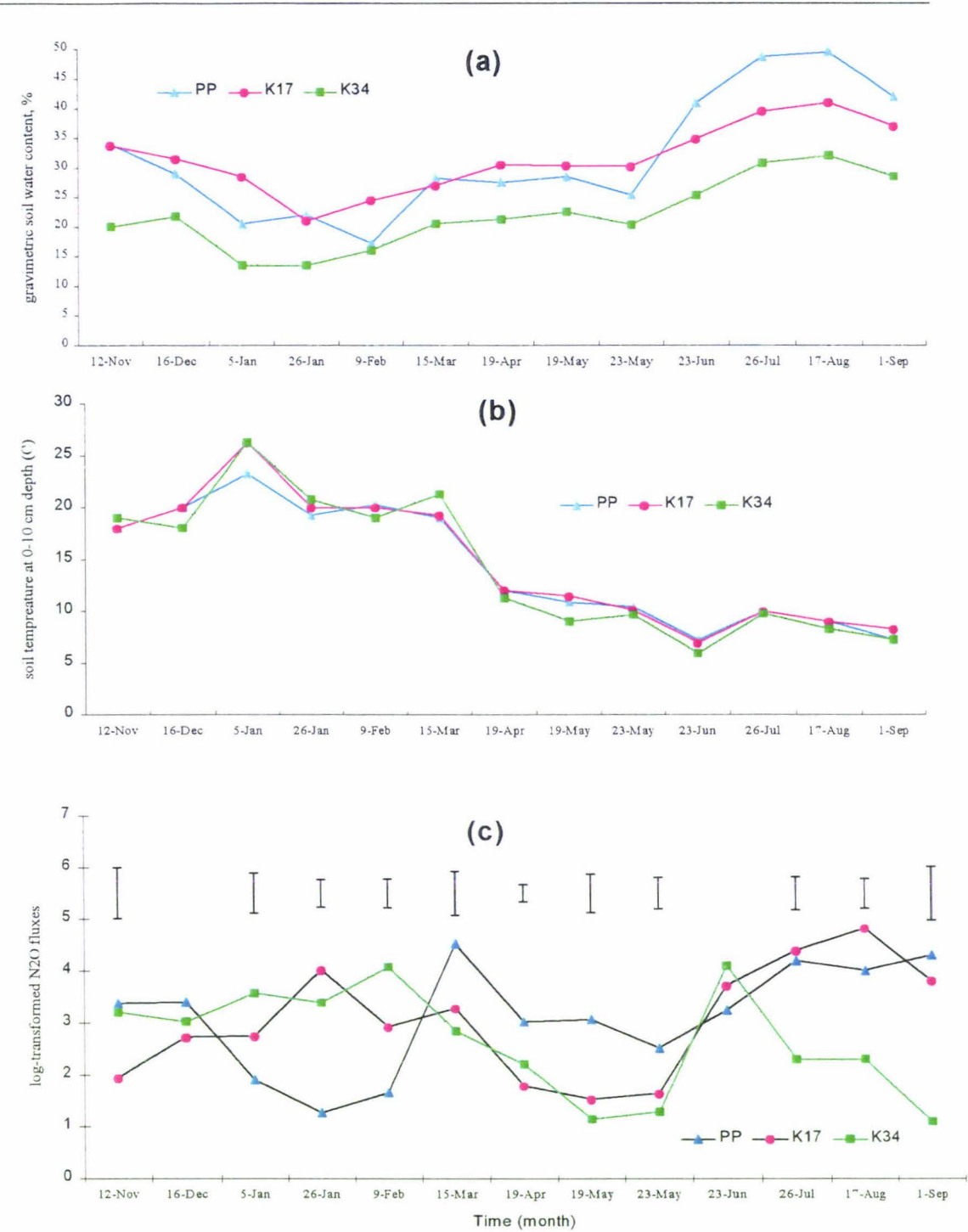


Figure 4.6 The effect of tillage treatment of the PP (permanent pasture), K17 (17 years continuous maize) and K34 (34 years of continuous maize) on the monthly data of soil moisture (a), temperature (b) and log-transformed means of N₂O emissions (c). (bars represent LSD)

Table 4.16: Soil moisture content at 0-10 cm depth during N₂O emission measurements.

	Gravimetric soil moisture content (%)												
Treat	12 Nov	16 Dec	5 Jan	26 Jan	9 Feb	15 Mar	19 Apr	19 May	23 May	23 Jun	26 Jul	17 Aug	1 Sep
PP	34 a	29 a	21 b	22 a	17 b	28 a	28 a	28 a	25 ab	41 a	49 a	50 a	42 a
K17	34 a	32 a	29 a	21 a	25 a	27 a	31 a	30 a	30 a	35 b	40 b	41 b	37 b
K34	20 b	22 b	14 c	14 b	16 b	21 b	21 b	22 b	20 b	25 c	31 c	32 c	29 c
LSD _{0.05}	2.18	3.00	1.77	1.41	2.37	3.98	3.72	2.85	5.24	3.09	1.36	3.06	1.77

Values followed by the same letter in the column show no significant difference (p<0.05)
PP = permanent pasture; K17 (K34) = 17 years (34 years) of conventional continuously grown maize

pattern. The SMC in the PP was also higher than in the K34, except few occasions. There were no marked differences between the K17 and PP fields until winter period.

During the June to early September period, SMC in the PP was substantially higher compared with the K17 and K34 fields. Low moisture content in all the treatments essentially reflected the low rainfall months during summer period. The SMC increased, not unexpectedly, with higher rainfall and colder temperatures during winter period.

It is well documented that pasture sites have higher water retention abilities. It was somewhat surprising though that there were no differences in the SMC between K17 and PP. However, K34 resulted in a lower soil moisture content in the field.

Effect of SMC on N₂O emissions in the K17 and PP were different than on the K34 (Figure 4.6). In the K34 field SMC did not seem to govern fluxes which were especially apparent during wet months of April and May. The regression analysis using the measured data revealed no relationship (r=0.12) between the SMC and N₂O fluxes in the K34 treatment (Figure 4.7). Nevertheless, the log-transformed values of N₂O emissions showed low negative correlation (r=-0.42) between the two parameters (Figure 4.8).

On the other hand, N₂O fluxes from the K17 and PP appeared to be influenced by soil moisture. There is clear indication (Figure 4.6) that low or negligible emissions occur

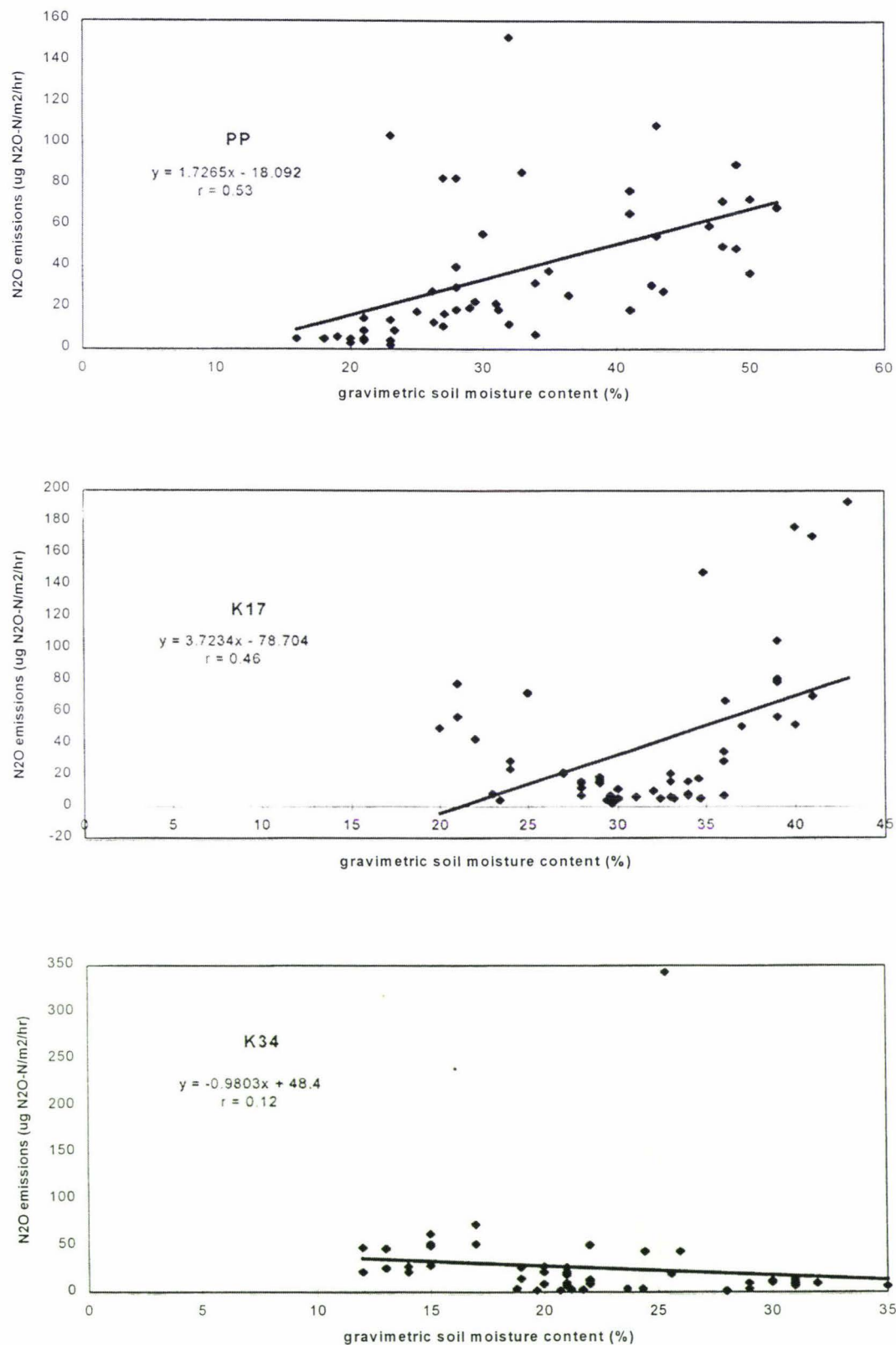


Figure 4.7 Regression analysis between measured soil moisture content and N₂O emissions in the PP (permanent pasture), K17 (17 years of continuous maize) and K34 (34 years of continuous maize) treatments.

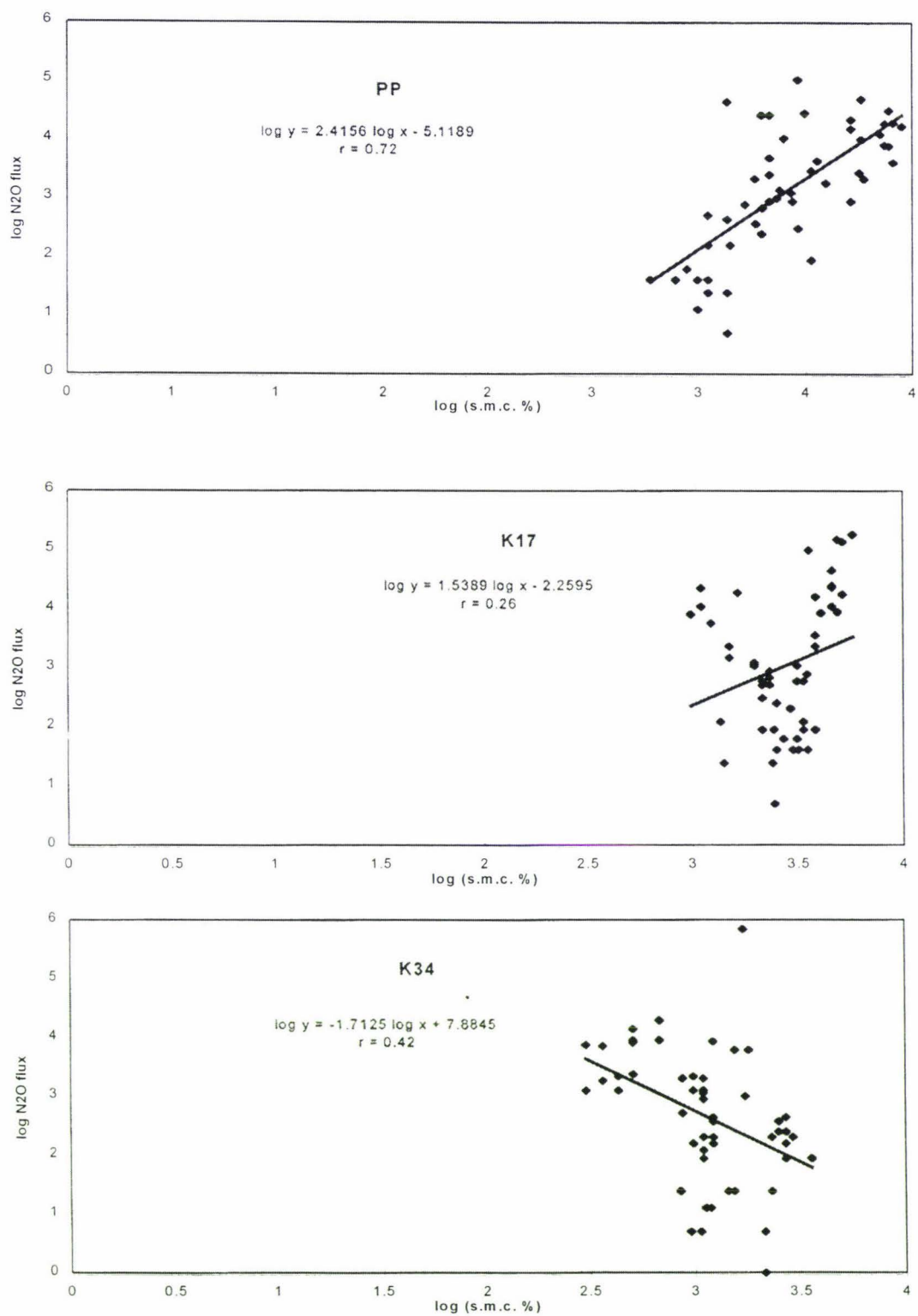


Figure 4.8 Regression analysis of log-transformed data between soil moisture content and N₂O emissions in the PP (permanent pasture), K17 (17 years of continuous maize) and K34 (34 years of continuous maize) treatments.

when gravimetric soil water content is less than 30%. Above this apparent threshold, the upper level of emission values increases with water content, but low values still occur frequently as observed by Carran et al. (1995). Although N₂O fluxes did not follow the rainfall patterns, linear regression analyses indicated low but significant relationship $r=0.46$ and 0.53 , respectively (Table 4.17). These results are similar to those reported by Kaiser et al. (1998) for arable soils and Carran et al. (1995) for pasture sites in these soils.

As the log-transformed values were thought to give rather strong correlation with SMC, regression analysis were conducted again. However, the analysis gave mixed results. The correlation in the PP was better ($R=0.72$) whereas no relationship was found in the K17 field.

Table 4.17: Correlation of soil moisture content with N₂O emission rates at the Kairanga field site.

Treatment	Measured data	Log-transformed data
	r values	r values
PP	0.53	0.72
K17	0.46	0.26
K34	0.12	0.42

PP = permanent pasture; K17 (K34) = 17 (34) years of conventional continuously grown maize

4.4.2.2 Seasonal Variation

General seasonal patterns of N₂O emissions at the Kairanga site were well defined for the PP, but less pronounced for the K17 and K34. In the PP, two periods of the year are obvious; low emissions during dry season while wet season values were substantially higher (Figure 4.6). The N₂O emissions pattern from the PP are consistent with the data of Carran et al. (1995) for the same soil type and the values for the wet season are similar to those recorded by Ruz-Jerez et al. (1994) in treatments not receiving fertiliser N.

Seasonal grouping of monthly log-transformed N₂O emissions showed significant differences in all treatments (Table 4.18). Summer season N₂O emissions in the PP were

the lowest than other seasons whereas no discernible differences were observed between other seasons, and were in the order of autumn=winter=spring.

Although N₂O fluxes during spring and summer were similar in the K17 field, they were significantly lower than the winter and higher than autumn fluxes, winter>spring=summer<autumn. There were considerably higher emissions in summer than in autumn in the K34 but seasonal variation between winter and spring was less profound.

Table 4.18: Seasonal log-transformed field N₂O emissions in the PP, CT and NT treatments.

Treatment	Field N ₂ O emissions				
	Spring (September- November)	Summer (December-January- February)	Autumn (March-April- May)	Winter (June-July- August)	LSD _{0.05}
PP	3.91 a	2.27 b	3.46 a	3.81 a	0.64
K17	3.01 b	3.08 b	2.23 c	4.31 a	0.66
K34	2.32 bc	3.53 a	2.09 c	2.90 ab	0.75

*Values followed by the same letter in the row show no significant differences (p<0.05)
PP = permanent pasture; K17 (K34) = 17 (34) years of conventional continuously grown maize*

Mixed N₂O flux response to seasonal variations between treatments makes it difficult to interpret these data. Therefore, seasonal effects on N₂O emissions in such treatments need to be considered separately. Similar pattern of the K17 and PP during wet season suggests that wet weather was a key determining factor, which was at its peak during the winter May-July period. However, opposite is true for the K34 N₂O emissions.

Apart from seasonal variation the data showed high monthly variations in N₂O emissions. For example, although the N₂O fluxes in the K34 were steadily decreasing from early autumn onward, and despite increasing soil moisture, recordings on June 23 were several orders higher than the previous measurement (Table 4.14). Again, the following measurement was several orders lower (Figure 4.6). Erratic nature of N₂O emissions are well recognised due to complexity of the processes and controlling factors involved.

Generally, processes responsible for high fluxes in the K17 and K34 compared to the PP in the aerobic soil conditions, indicate that these either did not occur in pasture soils or substrates required for reaction were not sufficient. Carran et al. (1995) postulated that the absence of significant emission events while the soil is dominantly aerobic suggested that nitrification or other transformations of urine-derived N do not contribute to overall emissions in an important way. This pattern suggests that denitrification was the primary source of N_2O in the PP.

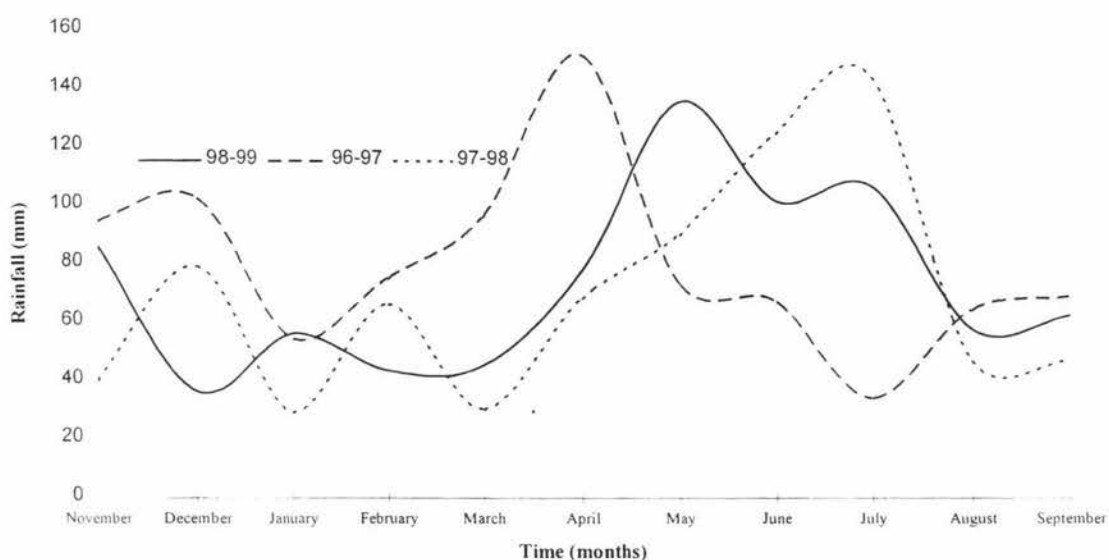


Figure 4.9 Monthly rainfall data for the Kairanga site from November 1998 to September 1999, 1996-97 and 1997-98. (note: rainfall data for 97-98 was used from another station located in close proximity)

Considering the last three years of rainfall pattern during the measurement period it is worth noting that the onset of wet season can be early, like in 1996-97, or late as in 1997-98 (Figure 4.9). While wet season fluxes in the K34 were generally low, high rainfall certainly influenced N_2O emissions in the K17 and PP fields. As it has been stressed earlier, wet season losses of N_2O may have considerable portion of total annual emissions from grazed pasture and cropped fields.

Distinctive performance of K34 and K17 during winter remains a problem and cannot be explained by the limited measurements of other ancillary factors. However, in the absence of measurement of nitrate levels, and considering results of this hypothesis tested by Carran et al. (1995) at similar soil types, which gave high response to addition

of NO_3 , the possibility that low N_2O emissions were limited by soil nitrate content remains.

4.4.2.3 Spatial Variation

Large spatial variation in N_2O fluxes was expected. Spatial variability of fluxes was large during the year with coefficients of variation (CV) ranging from 10 to 82%, 12 to 99% and 9 to 137% for the PP, K17 and K34 fields, respectively. The CV for grassland was lower than those reported by Williams et al. (1999) and higher compared to Carran et al. (1995). The CV for cropped fields were in accordance with those reported by Goodroad et al. (1984) and Kaiser et al. (1998).

Event-driven pulses of N_2O emissions have been reported often, which were also observed in this study. During last measurement on September 1 in the PP one of the chambers resulted in 10 g N_2O -N/ha/hr (~ 241 g/day) N_2O flux. It was approximately 10 to 20 times higher than N_2O emissions from the other three chambers. This high burst of N_2O was probably associated with urine and dung patches in the grazed pasture fields. However, it was considered as an outlier; and taking into account that such bursts are short-lived; and that there were no other similar bursts of N_2O flux measured throughout the study period; unlike Carran et al. (1995) who reported N_2O fluxes exceeding 400 g N_2O -N/ha/day from two sites; this figure was not included in the analysis.

Large variations observed could also be associated with the chamber sizes used. On the other hand, opting for larger size chambers may not eliminate the variability problem as noted by Ambus and Christensen (1994) that even N_2O fluxes obtained from “megachambers” (upward of 50 m²) should be interpreted carefully since they may not encompass the whole field variability. Williams et al. (1999) has further highlighted that even with decreased spatial variability there is also the question of diurnal variability.

High denitrification potential in these soils (Brian Daly, *pers. comm.*) and spatial variability of denitrification losses (Clayton et al., 1994) have already been stressed. Williams et al. (1999) advocates that a large number of cover boxes are required to obtain precise figure for the mean N_2O flux of a field. Thus, total annual N_2O emissions could only be presented with limited confidence and they must be interpreted with the understanding that they were calculated from short-term measurements during the day.

Also, there are temporal as well as spatial variability to be kept in mind. Nevertheless, the similarity of results indicate that despite variations in technique, treatments, and climate, the present results (Figure 4.6) could be used as boundary values (Table 4.12) for similar managed agricultural sites.

4.4.3 Summary

N₂O emissions from the treatment fields at Kairanga site were mixed. Overall tillage intensity had no effect on N₂O emissions from the PP, K17 and K34. Annual N₂O fluxes as low as 0.18 kg N₂O-N/ha can be expected from the PP and K17, and 0.09 kg N₂O-N/ha from the K34 fields. The highest N₂O emissions of 13.32, 16.91 and 30.05 kg N₂O-N kg/ha are also likely to occur in the PP, K17 and K34 fields during wet periods. The results suggest that N₂O emissions from the intensively grazed pasture are of the same magnitude as intensively cropped fields in the Manawatu Region, New Zealand.

Grazed pasture N₂O emissions were low during summer (dry) period and increased during winter (wet) season. There were no differences between the K17 and K34 N₂O fluxes during summer season but N₂O emission rates in winter were low in the K34 unlike N₂O emissions from the K17 field.

Negative soil moisture effect on N₂O fluxes from K34 field perhaps resulted from the interaction of several factors. Firstly, unlike the K17, total C content in the K34 was low which is used as an energy source by denitrifying microorganisms. Secondly, low level of total N in the K34 could have limited denitrification process. Continuous conventional maize cropping has further depleted nitrate level taking into account poor crop during measurement period. Furthermore, unlike the K17 field, there was no surface residue left in the K34 which could provide at least partial return of organic matter and nitrogen. Another factor is decreased water holding capacity of the K34 field soil which resulted from 34 years of cultivation. Low moisture content was probably not enough to create anaerobic condition.

Chapter 5

Conclusions

5.1 General

1. Spatial measurements of N_2O at the Massey site showed large inherent variations in N_2O fluxes (with CV between 110-127%) which reflected natural soil heterogeneity, and perhaps the measurement technique used rather than the real differences due the tillage and cropping systems evaluated.
2. Prolonged incubation of chambers appeared to result in slow diffusion rate over time and is not recommended. However, few samples per chamber should be allowed to monitor the chamber performance.

5.2 Massey Experimental Site (*Ohakea silt loam soil*)

1. Nitrous oxide (N_2O) emissions measured from December 1998 to September 1999 from the permanent pastureland (PP) were significantly lower (1.66 kg N_2O -N/ha/year) than conventional tillage (CT) and no-tillage (NT) plots at 9.20 and 12.00 kg N_2O -N/ha/year respectively. This indicates that conversion of pasture land to cropping and subsequent N fertilisation significantly increases N_2O gas emissions. The possible reason of rather low N_2O emissions from pasture paddocks could be low N inputs and higher N utilisation by the growing grasses, whereas in the CT and NT plots the roots distribution is not as dense as the proliferation of grass roots.
2. There were generally no differences in N_2O emission rates between the CT and NT treatments. Although there were some occasions when the NT had relatively, although insignificantly, higher fluxes than the CT in this study. This leads to conclusion that 4 years of continuous cropping with the NT is probably not sufficient time to allow pronounced differences to develop between these tillage methods.
3. The present study suggests that the annual fluxes as low as 0.09, 0.26 and 0.35 kg N_2O -N/ha could be expected from the PP, CT and NT management systems receiving fertiliser application in the North Island. Annual fluxes of as high as 6, 60

- and 65 kg N₂O-N/ha would also likely to occur in situations when soils are predisposed to give high bursts of emissions.
4. Seedbed preparation using power-harrow, which was done within few days of ploughing the CT plots, reduced N₂O emissions by 65% within the first hour after power-harrowing. Analysis of gas samples for up to 9 hours suggested that gas fluxes remained low. This clearly supports the view that ploughing and secondary cultivation increases aeration, enhances moisture evapotranspiration and subsequently reduces denitrification rate. However, N₂O emission rates returned to the pre-power harrowing levels one month after power-harrowing which most likely was associated with increased soil moisture content and recompaction.
 5. Tillage practices generally influenced water content in all treatments during different months of the year. The NT plots had higher moisture content compared to the CT and PP plots during summer and early autumn when rainfall events were not frequent. Lower moisture content in the PP could be due to high transpiration rate from the growing pasture. However, during winter period soil moisture in the PP was generally higher compared to the NT and CT plots. This could be associated with generally less evapotranspiration unlike during summer time.
 6. There was strong relationship between soil moisture content and N₂O emissions in all treatments. The log-transformed N₂O data showed high correlation with field soil moisture with the PP ($r = 0.73$), CT ($r = 0.75$) and NT ($r = 0.86$). These relationships indicated that field soil moisture content generally, although partially, determined the N₂O emissions.
 7. Seasonal variation in N₂O emission from the PP was in the order of winter=autumn>summer. Although fluxes in the CT were higher in winter than in the autumn season, there were no differences between the summer and autumn data. Similar to pasture, the seasonal variations in N₂O emission in the NT treatment were in the order of winter>autumn=summer.
 8. Cropping using CT resulted in marked decline in total C (21%) and N (17%) in top 0-10 cm depth in the CT field compared to the PP. Similarly, the total C and pH

declined in the NT by 12 and 4% respectively. Nevertheless, although at 10-20 cm soil depth, total C and N were lower in all treatments, these were distributed reasonably even in all plots. The higher amount of total C (11%) in the NT as compared to the CT treatment was possibly due to high retention of crop residue over the soil surface, less disturbance and subsequently less erosion.

9. Coefficient of variation (CV) of N_2O emissions for treatments ranged from 39 to 140%.

5.3 Kairanga Experimental Site (*Kairanga silt loam soil*)

1. The estimated annual N_2O emissions from the PP, K17 and K34 (calculated as the mean of all individual closed cover chamber measurements between November 1998 and September 1999) were statistically similar at 3.24, 3.42 and 2.37 kg N_2O -N/ha/year, respectively.
2. There were large variations in N_2O emissions during the year with the mean flux rates ranging from 0.175 to 13.32, 0.175 to 16.91 and 0.088 to 30.05 kg N_2O -N/ha/year in the PP, K17 and K34 fields, respectively.
3. Although overall comparison of treatment means did not show any discernible differences between management practices, there were signs that the K34 had lower emissions compared to the PP. Fluctuations in N_2O fluxes throughout the sampling period were the possible explanation for this. Higher N_2O fluxes in the PP could be associated with pastoral management (dairy) system used.
4. Soil moisture content (SMC) was significantly affected by the tillage treatments throughout the year. The K34 field SMC was always 22 to 52% lower compared to the K17 field. The SMC in the PP was also higher than in the K34, except few occasions. There were no marked differences between the K17 and PP fields until winter period.
5. N_2O fluxes from the K17 and PP field appeared to be influenced by soil moisture. There is clear indication that low or negligible emissions occur when gravimetric soil water content is less than 30% in the PP. Although N_2O fluxes did not follow the

rainfall patterns in the K17 and PP, linear regression analyses indicated low but significant relationship $r=0.46$ and 0.53 (0.72 when log-transformed), respectively.

6. In the K34 field, SMC did not seem to govern fluxes which were especially apparent during wet months of April and May. The linear regression analysis using the measured data revealed no relationship ($r=0.12$) between the SMC and N_2O fluxes in the K34 treatment.
7. Seasonal grouping of monthly log-transformed N_2O emissions showed significant differences in all treatments. Summer season N_2O emissions in the PP were the lowest than other seasons whereas no discernible differences were observed between other seasons, and were in the order of autumn=winter=spring. Although N_2O fluxes during spring and summer were similar in the K17 field, they were significantly lower than the winter and higher than autumn fluxes, winter>spring=summer<autumn. There were considerably higher emissions in summer than in autumn in the K34 but seasonal variation between winter and spring was less profound.
8. Spatial variability of fluxes was large during the year with coefficients of variation (CV) ranging from 10 to 82%, 12 to 99% and 9 to 137% for the PP, K17 and K34 fields, respectively.

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Appendix I

Table I-1. Ohakea silt loam soil total C, N and pH of the Massey experimental site.

Treatment	Total C (%)	Total N (%)	pH 1:2.5 soil:water	Total C (%)	Total N (%)	pH 1:2.5 soil:water
	0-10 cm depth			10-20 cm depth		
PP	2.50	0.17	5.41	1.85	0.17	5.35
	2.80	0.18	5.32	1.90	0.18	5.35
	2.83	0.17	5.31	1.85	0.17	5.33
	2.85	0.16	5.18	1.75	0.16	5.26
CT	2.22	0.21	5.44	1.99	0.20	5.40
	2.27	0.23	5.28	1.92	0.18	5.35
	2.12	0.20	5.14	1.83	0.17	5.12
	2.07	0.18	5.35	1.99	0.19	5.15
NT	2.40	0.23	5.08	1.86	0.18	5.08
	2.64	0.24	5.23	1.95	0.19	5.09
	2.29	0.21	5.06	1.74	0.16	5.11
	2.40	0.21	5.01	1.66	0.16	5.11

ANALYSIS: COMPARISON OF TREATMENTS

General Linear Models Procedure

Dependent Variable: C10 C (%) at 0-10 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.66291667	0.33145833	17.37	0.0008
Error	9	0.17177500	0.01908611		
Corrected Total	11	0.83469167			
R-Square C.V. Root MSE C10 Mean					
0.794205 5.640796 0.13815249 2.44916667					
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.66291667	0.33145833	17.37	0.0008
Dependent Variable: C20 C (%) at 10-20 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.03620000	0.01810000	2.08	0.1813
Error	9	0.07842500	0.00871389		
Corrected Total	11	0.11462500			
R-Square C.V. Root MSE C20 Mean					
0.315812 5.025476 0.09334821 1.85750000					
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.03620000	0.01810000	2.08	0.1813
Dependent Variable: N10 N (%) at 0-10 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.00281667	0.00140833	4.78	0.0384
Error	9	0.00265000	0.00029444		
Corrected Total	11	0.00546667			
R-Square C.V. Root MSE N10 Mean					

	0.515244	7.683306	0.01715938	0.22333333	
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.00281667	0.00140833	4.78	0.0384
Dependent Variable: N20 N (%) at 10-20 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.00051667	0.00025833	1.69	0.2380
Error	9	0.00137500	0.00015278		
Corrected Total	11	0.00189167			
	R-Square	C.V.	Root MSE	N20 Mean	
	0.273128	7.029572	0.01236033	0.17583333	
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.00051667	0.00025833	1.69	0.2380
Dependent Variable: PH10 pH at 0-10 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.11621667	0.05810833	5.13	0.0325
Error	9	0.10187500	0.01131944		
Corrected Total	11	0.21809167			
	R-Square	C.V.	Root MSE	PH10 Mean	
	0.532880	2.032661	0.10639288	5.23416667	
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.11621667	0.05810833	5.13	0.0325
Dependent Variable: PH20 pH at 10-20 cm					
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	0.10665000	0.05332500	7.33	0.0129
Error	9	0.06545000	0.00727222		
Corrected Total	11	0.17210000			
	R-Square	C.V.	Root MSE	PH20 Mean	
	0.619698	1.632102	0.08527733	5.22500000	
Source	DF	Type I SS	Mean Square	F Value	Pr > F
TREAT	2	0.10665000	0.05332500	7.33	0.0129

Table I-2: Results of prolonged measurements of N₂O concentration in a closed chamber over time in the treatments at Massey experimental site.

Treatment	1 st hour	2 nd hour	3 rd hour	5 th hour	7 th hour	9 th hour
	µg N ₂ O-N/m ² /hour					
Conventional Tillage (CT)						
R ₁	36	28	20	21	21	18
R ₂	31	25	20	17	14	12
R ₃	36	29	25	28	19	16
R ₄	14	12	11	10	8	7
No-Tillage (NT)						
R ₁	33	26	23	27	23	17
R ₂	21	18	18	19	16	14
R ₃	16	14	14	15	14	12
R ₄	60	54	56	66	60	54
Permanent Pasture (PP)						
R ₁	7	5	5	11	4	3
R ₂	19	16	14	11	13	12
R ₃	16	11	11	25	13	8
R ₄	14	12	12	12	10	9

Table I-3. Effects of tillage systems on N₂O emissions at Massey site from December 1998 to September 1999. (Values are the means of t₁, t₂ & t₃)

Treatment	22 Dec	7 Jan	29 Jan	11 Feb	18 Mar	22 Apr	16 Jun	28 Jul	19 Aug	8 Sep
µg N ₂ O-N/m ² /hour										
Permanent Pasture (PP)										
R ₁	16	8	2	1	6	51	18	38	7	60
R ₂	33	5	3	1	16	51	40	26	17	26
R ₃	11	7	2	1	13	5	21	28	7	69
R ₄	15	6	3	1	13	9	43	45	7	15
Conventional Tillage (CT)										
R ₁	199	57	12	7	72	163	56	39	35	56
R ₂	192	18	26	10	76	71	182	238	684	94
R ₃	166	11	13	7	44	38	184	157	123	152
R ₄	428	21	6	3	65	32	335	36	34	231
No-Tillage (NT)										
R ₁	84	27	16	4	28	72	320	547	351	213
R ₂	130	48	23	15	19	24	88	341	170	107
R ₃	36	18	16	9	15	20	184	741	175	266
R ₄	353	20	27	7	57	21	382	398	52	95

ANALYSIS: OVERALL COMPARISON OF MEASURED N₂O EMISSIONS BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: N₂O emissions

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	303474.050000	9.43	0.0002
Error	117	1883278.750000		
Corrected Total	119	2186752.800000		

R-Square	C.V.	N2O Mean
0.138778	145.6620	87.1000000

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	303474.050000	9.43	0.0002

ANALYSIS: COMPARISON OF LOG-TRANSFORMED N₂O EMISSIONS ON EACH SAMPLING DATE BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: LDATE1 Dec-22

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	14.18877866	16.37	0.0010
Error	9	3.90076534		
Corrected Total	11	18.08954401		

R-Square	C.V.	LDATE1 Mean
0.784364	15.23792	4.32044093

Source	DF	Type I SS	F Value	Pr > F
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TREAT	2	14.18877866	16.37	0.0010
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Dependent Variable: LDATE2 Jan-7

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	4.71773098	9.95	0.0052
Error	9	2.13337087		
Corrected Total	11	6.85110186		

R-Square	C.V.	LDATE2 Mean
0.688609	17.78217	2.73796098

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	4.71773098	9.95	0.0052

Dependent Variable: LDATE3 Jan-29

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	9.70211763	30.07	0.0001
Error	9	1.45184952		
Corrected Total	11	11.15396715		

R-Square	C.V.	LDATE3 Mean
0.869836	18.78316	2.13831162

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	9.70211763	30.07	0.0001

Dependent Variable: LDATE4 Feb-11

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	10.16134830	27.05	0.0002
Error	9	1.69064681		
Corrected Total	11	11.85199511		

R-Square	C.V.	LDATE4 Mean
0.857353	33.48892	1.29420808

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	10.16134830	27.05	0.0002

Dependent Variable: LDATE5 Mar-18

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	5.90432971	15.04	0.0013
Error	9	1.76637884		
Corrected Total	11	7.67070854		

R-Square	C.V.	LDATE5 Mean
0.769724	13.53139	3.27399735

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	5.90432971	15.04	0.0013

Dependent Variable: LDATE6 Apr-22

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	2.92150108	1.87	0.2090
Error	9	7.02160789		
Corrected Total	11	9.94310897		

R-Square	C.V.	LDATE6 Mean
0.293822	25.46382	3.46875338

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	2.92150108	1.87	0.2090

Dependent Variable: LDATE7 Jun-16

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	9.40819819	11.82	0.0030
Error	9	3.58160366		
Corrected Total	11	12.98980185		

R-Square	C.V.	LDATE7 Mean
0.724276	13.75137	4.58745105

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	9.40819819	11.82	0.0030

Dependent Variable: LDATE8 Jul-28

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	14.73162382	19.86	0.0005
Error	9	3.33833277		
Corrected Total	11	18.06995659		

R-Square	C.V.	LDATE8 Mean
0.815255	12.92593	4.71174422

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	14.73162382	19.86	0.0005

Dependent Variable: LDATE9 Aug-19

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	19.07089126	10.12	0.0050
Error	9	8.47967198		
Corrected Total	11	27.55056324		

R-Square	C.V.	LDATE9 Mean
0.692214	24.67503	3.93378408

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	19.07089126	10.12	0.0050

Dependent Variable: LDATE10 Sep-8

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	4.85837873	6.34	0.0191
Error	9	3.44786659		
Corrected Total	11	8.30624531		

R-Square	C.V.	LDATE10 Mean
0.584907	13.88267	4.45841973

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	4.85837873	6.34	0.0191

ANALYSIS: COMPARISON OF SEASONAL LOG-TRANSFORMED N₂O EMISSIONS BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: LCT Conventional tillage

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	2.60115717	3.06	0.0969
Error	9	3.82549721		
Corrected Total	11	6.42665439		

R-Square	C.V.	LCT Mean
0.404745	15.13541	4.30753068

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	2.60115717	3.06	0.0969

Dependent Variable: LNT No-till				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	12.46038993	22.38	0.0003
Error	9	2.50539463		
Corrected Total	11	14.96578456		
	R-Square	C.V.	LNT Mean	
	0.832592	12.31259	4.28516493	

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	12.46038993	22.38	0.0003

Dependent Variable: LPP Permanent pasture				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	3.36215124	8.62	0.0081
Error	9	1.75608182		
Corrected Total	11	5.11823306		
	R-Square	C.V.	LPP Mean	
	0.656897	16.58774	2.66295464	

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	3.36215124	8.62	0.0081

Table I-4. Effect of tillage techniques on gravimetric soil moisture content (%) at 0-10 cm depth during N₂O emission measurements at Massey site.

Treatment	22 Dec	7 Jan	29 Jan	11 Feb	18 Mar	22 Apr	16 Jun	28 Jul	19 Aug	8 Sep
Permanent Pasture (PP)										
R ₁	26	12	11	10	15	19	33	36	37	33
R ₂	27	12	11	9	14	19	35	38	41	31
R ₃	26	12	11	10	15	22	35	40	40	33
R ₄	27	12	11	10	14	22	36	41	43	35
Conventional Tillage (CT)										
R ₁	24	11	11	9	17	25	29	31	30	27
R ₂	23	10	10	10	15	23	32	31	30	29
R ₃	24	11	11	10	15	23	33	30	30	26
R ₄	23	10	10	10	15	21	33	32	31	27
No-Tillage (NT)										
R ₁	30	16	15	10	17	21	31	31	35	28
R ₂	30	18	15	11	17	20	33	32	35	28
R ₃	30	16	15	13	18	22	33	33	33	27
R ₄	30	18	15	12	18	22	33	34	37	27

ANALYSIS: COMPARISON OF SOIL MOISTURE CONTENT BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: MOIST1

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	84.66666667	190.50	0.0001
Error	9	2.00000000		
Corrected Total	11	86.66666667		

R-Square	C.V.	MOIST1 Mean
0.976923	1.767767	26.6666667

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	84.66666667	190.50	0.0001

Dependent Variable: MOIST2

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	92.66666667	83.40	0.0001
Error	9	5.00000000		
Corrected Total	11	97.66666667		

R-Square	C.V.	MOIST2 Mean
0.948805	5.660932	13.1666667

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	92.66666667	83.40	0.0001

Dependent Variable: MOIST3

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	48.66666667	219.00	0.0001
Error	9	1.00000000		
Corrected Total	11	49.66666667		

	R-Square	C.V.	MOIST3 Mean	
	0.979866	2.739726	12.1666667	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	48.66666667	219.00	0.0001
Dependent Variable: MOIST4				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	8.16666667	5.65	0.0257
Error	9	6.50000000		
Corrected Total	11	14.66666667		
	R-Square	C.V.	MOIST4 Mean	
	0.556818	8.224225	10.3333333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	8.16666667	5.65	0.0257
Dependent Variable: MOIST5				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	18.66666667	16.80	0.0009
Error	9	5.00000000		
Corrected Total	11	23.66666667		
	R-Square	C.V.	MOIST5 Mean	
	0.788732	4.707512	15.8333333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	18.66666667	16.80	0.0009
Dependent Variable: MOIST6				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	13.16666667	3.00	0.1004
Error	9	19.75000000		
Corrected Total	11	32.91666667		
	R-Square	C.V.	MOIST6 Mean	
	0.400000	6.863471	21.5833333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	13.16666667	3.00	0.1004
Dependent Variable: MOIST7				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	19.50000000	4.74	0.0392
Error	9	18.50000000		
Corrected Total	11	38.00000000		
	R-Square	C.V.	MOIST7 Mean	
	0.513158	4.344609	33.0000000	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	19.50000000	4.74	0.0392
Dependent Variable: MOIST8				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	135.16666667	27.97	0.0001
Error	9	21.75000000		
Corrected Total	11	156.91666667		
	R-Square	C.V.	MOIST8 Mean	

	0.861391	4.561066	34.0833333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	135.16666667	27.97	0.0001
Dependent Variable: MOIST9				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	200.16666667	32.75	0.0001
Error	9	27.50000000		
Corrected Total	11	227.66666667		
	R-Square	C.V.	MOIST9 Mean	
	0.879209	4.970658	35.1666667	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	200.16666667	32.75	0.0001
Dependent Variable: MOIST10				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	84.50000000	27.65	0.0001
Error	9	13.75000000		
Corrected Total	11	98.25000000		
	R-Square	C.V.	MOIST10 Mean	
	0.860051	4.225754	29.2500000	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	84.50000000	27.65	0.0001

Appendix II

Table II-1. Effects of tillage systems on N₂O emissions at Kairanga site from November 1998 to September 1999. (Values are the means of t₁, t₂ & t₃)

	12	16	5	26	9	15	19	19	23	23	26	17	1
	Nov	Dec	Jan	Jan	Feb	Mar	Apr	May	May	Jun	Jul	Aug	Sep
µg N ₂ O-N/m ² /hour													
Permanent Pasture (PP)													
R ₁	38	83	15	4	5	104	22	19	9	28	73	50	55
R ₂	7	12	5	2	6	56	14	23	11	26	49	69	77
R ₃	86	20	9	5	5	152	30	17	18	31	90	37	66
R ₄	32	40	3	4	5	83	19	28	13	19	60	72	109
17 years of continuous maize (K17)													
R ₁	8	10	15	50	21	72	5	4	5	148	57	70	79
R ₂	7	16	17	43	24	21	6	11	5	18	81	193	35
R ₃	7	16	12	78	8	22	7	5	7	16	52	171	51
R ₄	6	21	19	57	29	15	6	2	4	67	177	105	29
34 years of continuous maize (K34)													
R ₁	22	51	48	47	50	27	8	2	2	343	11	13	2
R ₂	27	19	52	22	52	15	9	3	4	44	9	10	1
R ₃	22	14	22	26	73	21	10	4	3	20	14	11	10
R ₄	28	13	29	28	63	10	9	4	7	44	7	7	4

ANALYSIS: OVERALL COMPARISON OF LOG-TRANSFORMED N₂O EMISSIONS BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: LN20

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	6.17461856	2.45	0.0895
Error	153	192.65593490		
Corrected Total	155	198.83055345		

R-Square	C.V.	LN20 Mean
0.031055	38.29549	2.93020404

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	6.17461856	2.45	0.0895

ANALYSIS: COMPARISON OF LOG-TRANSFORMED N₂O EMISSIONS ON EACH SAMPLING DATE BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: LDATE1

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	4.90901287	6.54	0.0176
Error	9	3.37633705		
Corrected Total	11	8.28534992		

R-Square	C.V.	LDATE1 Mean
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	0.592493	21.56875	2.83972726	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	4.90901287	6.54	0.0176
Dependent Variable: LDATE2				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	0.91287125	1.14	0.3614
Error	9	3.59664915		
Corrected Total	11	4.50952041		
	R-Square	C.V.	LDATE2 Mean	
	0.202432	20.74875	3.04674294	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	0.91287125	1.14	0.3614
Dependent Variable: LDATE3				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	5.55696705	11.96	0.0029
Error	9	2.09099905		
Corrected Total	11	7.64796610		
	R-Square	C.V.	LDATE3 Mean	
	0.726594	17.59977	2.73872643	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	5.55696705	11.96	0.0029
Dependent Variable: LDATE4				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	16.57669132	75.41	0.0001
Error	9	0.98919559		
Corrected Total	11	17.56588691		
	R-Square	C.V.	LDATE4 Mean	
	0.943687	11.47166	2.88997068	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	16.57669132	75.41	0.0001
Dependent Variable: LDATE5				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	11.71243687	47.63	0.0001
Error	9	1.10655178		
Corrected Total	11	12.81898865		
	R-Square	C.V.	LDATE5 Mean	
	0.913679	12.16585	2.88218731	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	11.71243687	47.63	0.0001
Dependent Variable: LDATE6				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	6.14747716	11.10	0.0037
Error	9	2.49146185		
Corrected Total	11	8.63893901		
	R-Square	C.V.	LDATE6 Mean	
	0.711601	14.82666	3.54864496	

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	6.14747716	11.10	0.0037
Dependent Variable: LDATE7				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	3.16162986	37.15	0.0001
Error	9	0.38292100		
Corrected Total	11	3.54455086		
	R-Square	C.V.	LDATE7 Mean	
	0.891969	8.842905	2.33258991	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	3.16162986	37.15	0.0001
Dependent Variable: LDATE8				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	8.27030415	19.11	0.0006
Error	9	1.94753209		
Corrected Total	11	10.21783624		
	R-Square	C.V.	LDATE8 Mean	
	0.809399	24.38000	1.90803950	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	8.27030415	19.11	0.0006
Dependent Variable: LDATE9				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	3.21269678	11.57	0.0033
Error	9	1.24989517		
Corrected Total	11	4.46259196		
	R-Square	C.V.	LDATE9 Mean	
	0.719917	20.58388	1.81045711	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	3.21269678	11.57	0.0033
Dependent Variable: LDATE10				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	1.47865949	0.83	0.4672
Error	9	8.02439533		
Corrected Total	11	9.50305482		
	R-Square	C.V.	LDATE10 Mean	
	0.155598	25.61509	3.68628622	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	1.47865949	0.83	0.4672
Dependent Variable: LDATE11				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	10.71926101	34.57	0.0001
Error	9	1.39538006		
Corrected Total	11	12.11464107		
	R-Square	C.V.	LDATE11 Mean	
	0.884819	10.85684	3.62678460	
Source	DF	Type I SS	F Value	Pr > F

TREAT	2	10.71926101	34.57	0.0001
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Dependent Variable: LDATE12

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	13.26470352	51.96	0.0001
Error	9	1.14877569		
Corrected Total	11	14.41347921		

R-Square	C.V.	LDATE12 Mean
0.920299	9.623028	3.71265523

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	13.26470352	51.96	0.0001

Dependent Variable: LDATE13

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	23.89208359	28.71	0.0001
Error	9	3.74486089		
Corrected Total	11	27.63694448		

R-Square	C.V.	LDATE13 Mean
0.864498	21.01265	3.06984044

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	23.89208359	28.71	0.0001

ANALYSIS: COMPARISON OF SEASONAL LOG-TRANSFORMED N₂O EMISSIONS BETWEEN TREATMENTS
General Linear Models Procedure

Dependent Variable: LPP

Source	DF	Sum of Squares	F Value	Pr > F
Model	3	20.51948210	11.37	0.0001
Error	44	26.47212096		
Corrected Total	47	46.99160306		

R-Square	C.V.	LPP Mean
0.436663	23.05398	3.36451269

Source	DF	Type I SS	F Value	Pr > F
TREAT	3	20.51948210	11.37	0.0001

Dependent Variable: LK17

Source	DF	Sum of Squares	F Value	Pr > F
Model	3	26.70628601	14.13	0.0001
Error	44	27.71917424		
Corrected Total	47	54.42546024		

R-Square	C.V.	LK17 Mean
0.490695	25.15625	3.15513496

Source	DF	Type I SS	F Value	Pr > F
TREAT	3	26.70628601	14.13	0.0001

Dependent Variable: LK34

Source	DF	Sum of Squares	F Value	Pr > F
Model	3	15.05527859	6.08	0.0015
Error	44	36.30674629		
Corrected Total	47	51.36202488		

R-Square	C.V.	LK34 Mean
0.293121	33.51695	2.71020950

Source	DF	Type I SS	F Value	Pr > F
TREAT	3	15.05527859	6.08	0.0015

Table II-2. Effect of tillage techniques on gravimetric soil moisture content (%) at 0-10 cm depth during N₂O emission measurements at Massey site.

	12 Nov	16 Dec	5 Jan	26 Jan	9 Feb	15 Mar	19 Apr	19 May	23 May	23 Jun	26 Jul	17 Aug	1 Sep
Permanent Pasture (PP)													
R ₁	35	27	21	21	16	23	31	31	23	44	50	48	43
R ₂	34	32	20	23	19	30	23	29	27	37	49	52	41
R ₃	33	29	21	21	18	32	28	27	25	43	49	50	41
R ₄	34	28	20	23	16	28	28	26	26	41	47	48	43
17 years of continuous maize (K17)													
R ₁	34	32	28	20	27	25	30	29	33	35	39	41	39
R ₂	36	28	29	22	24	27	33	30	35	35	39	43	36
R ₃	34	33	28	21	23	27	28	32	30	34	40	41	37
R ₄	31	33	29	21	24	29	31	30	23	36	40	39	36
34 years of continuous maize (K34)													
R ₁	21	22	12	13	15	21	21	21	20	25	30	30	28
R ₂	19	21	15	14	17	19	20	21	19	24	31	32	28
R ₃	20	22	12	13	17	21	22	24	22	26	31	31	29
R ₄	20	22	15	14	15	21	22	24	21	26	31	35	29

ANALYSIS: COMPARISON OF SOIL MOISTURE CONTENT BETWEEN TREATMENTS

General Linear Models Procedure

Dependent Variable: MOIST1 Nov-12				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	513.50000000	137.96	0.0001
Error	9	16.75000000		
Corrected Total	11	530.25000000		

R-Square	C.V.	MOIST1 Mean
0.968411	4.664019	29.2500000

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	513.50000000	137.96	0.0001

Dependent Variable: MOIST2 Dec-16				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	205.16666667	29.08	0.0001
Error	9	31.75000000		
Corrected Total	11	236.91666667		

R-Square	C.V.	MOIST2 Mean
0.865987	6.850716	27.4166667

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	205.16666667	29.08	0.0001

Dependent Variable: MOIST3 Jan-5				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	450.66666667	184.36	0.0001
Error	9	11.00000000		
Corrected Total	11	461.66666667		

R-Square C.V. MOIST3 Mean
0.976173 5.306600 20.833333

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	450.66666667	184.36	0.0001

Dependent Variable: MOIST4 Jan-26

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	172.66666667	111.00	0.0001
Error	9	7.00000000		
Corrected Total	11	179.66666667		

R-Square C.V. MOIST4 Mean
0.961039 4.682746 18.833333

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	172.66666667	111.00	0.0001

Dependent Variable: MOIST5 Feb-9

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	168.50000000	38.39	0.0001
Error	9	19.75000000		
Corrected Total	11	188.25000000		

R-Square C.V. MOIST5 Mean
0.895086 7.695406 19.250000

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	168.50000000	38.39	0.0001

Dependent Variable: MOIST6 Mar-15

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	138.50000000	11.18	0.0036
Error	9	55.75000000		
Corrected Total	11	194.25000000		

R-Square C.V. MOIST6 Mean
0.712999 9.856887 25.250000

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	138.50000000	11.18	0.0036

Dependent Variable: MOIST7 Apr-19

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	178.16666667	16.45	0.0010
Error	9	48.75000000		
Corrected Total	11	226.91666667		

R-Square C.V. MOIST7 Mean
0.785163 8.810246 26.416667

Source	DF	Type I SS	F Value	Pr > F
TREAT	2	178.16666667	16.45	0.0010

Dependent Variable: MOIST8 May-19

Source	DF	Sum of Squares	F Value	Pr > F
Model	2	129.50000000	20.45	0.0004
Error	9	28.50000000		
Corrected Total	11	158.00000000		

	R-Square	C.V.	MOIST8 Mean	
	0.819620	6.590789	27.0000000	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	129.50000000	20.45	0.0004
Dependent Variable: MOIST9				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	190.16666667	8.87	0.0075
Error	9	96.50000000		
Corrected Total	11	286.66666667		
	R-Square	C.V.	MOIST9 Mean	
	0.663372	12.92558	25.3333333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	190.16666667	8.87	0.0075
Dependent Variable: MOIST10				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	520.16666667	69.87	0.0001
Error	9	33.50000000		
Corrected Total	11	553.66666667		
	R-Square	C.V.	MOIST10 Mean	
	0.939494	5.702383	33.8333333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	520.16666667	69.87	0.0001
Dependent Variable: MOIST11				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	648.16666667	448.73	0.0001
Error	9	6.50000000		
Corrected Total	11	654.66666667		
	R-Square	C.V.	MOIST11 Mean	
	0.990071	2.142445	39.6666667	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	648.16666667	448.73	0.0001
Dependent Variable: MOIST12				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	612.66666667	83.55	0.0001
Error	9	33.00000000		
Corrected Total	11	645.66666667		
	R-Square	C.V.	MOIST12 Mean	
	0.948890	4.689439	40.8333333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	612.66666667	83.55	0.0001
Dependent Variable: MOIST13				
Source	DF	Sum of Squares	F Value	Pr > F
Model	2	372.66666667	152.45	0.0001
Error	9	11.00000000		
Corrected Total	11	383.66666667		
	R-Square	C.V.	MOIST13 Mean	
	0.971329	3.085232	35.8333333	
Source	DF	Type I SS	F Value	Pr > F
TREAT	2	372.66666667	152.45	0.0001