Anadolu Tarım Bilim. Derg., 2010,25(S-2):94-101
Anadolu J. Agric. Sci., 2010,25(S-2):94-101

Research
Araştırma

EMISSIONS OF NITROUS OXIDE FROM ARABLE SOILS: EFFECTS OF TILLAGE REDUCED N INPUT AND CLIMATE CHANGE

M. ABDALLA[1,*] M. JONES[1] P. AMBUS[2] M. WATTENBACH[3] P. SMITH[3] M. WILLIAMS[1]

[1] Department of Botany, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland
[2] Technical University of Denmark, Risoe National Laboratory for Sustainable Energy, Denmark
[3] School of Biological Sciences, University of Aberdeen, St. Machar Drive, Aberdeen, AB24 3UU, UK
***e-mail: abdallm@tcd.ie**

Abstract: Nitrous oxide (N_2O) flux measurements from an Irish spring barley field managed under conventional and reduced tillage and different N fertilizer rates at the Teagasc Oak Park Research Centre were made for two consecutive seasons. The aims were to investigate the efficacy of reduced tillage, reduced N fertilizer and climate change on N_2O fluxes and emission factors and to study the relationship between crop yield and N-induced fluxes of N_2O. The soil is a sandy loam with a pH of 7.4 and organic carbon and nitrogen content at 15 cm of 19 and 1.9 g kg^{-1} dry soil, respectively. Three climate scenarios, a baseline of measured climatic data from a nearby weather station and a high and low temperature sensitive scenarios predicted by the Hadley Global Climate Model were investigated. The Field-DeNitrification DeComposition (DNDC) was tested against measured nitrous oxide flux from the field, and then used to estimate future fluxes. Reduced tillage had no significant effect on N_2O fluxes from soils or crop grain yield. Soil moisture and soil nitrate are the main significant factors affecting N_2O flux. The derived emission factor was 0.6% of the applied N fertilizer. By reducing the applied nitrogen fertilizer by 50 % compared to the normal field rate, N_2O emissions could be reduced by 57% with no significant decrease on grain yield or quality. DNDC was found suitable to estimate N_2O fluxes from Irish arable soils however, underestimated the flux by 24%. Under climate change, using the high temperature increase scenario, DNDC predicted an increase in N_2O emissions from both conventional and reduced tillage, ranging from 58 to 88% depending upon N application rate. In contrast annual fluxes of N_2O either decreased or increased slightly in the low temperature increase scenario relative to N application (-26 to +16%). Outputs from the model indicate that elevated temperature and precipitation increase N mineralisation and total denitrification leading to greater fluxes of N_2O. Annual uncertainties due to the use of two different future climate scenarios were significantly high, ranging from 74 to 95% and from 71 to 90% for the conventional and reduced tillage respectively.
Key Words: Nitrous oxide, Conventional tillage, Reduced tillage, Spring barley, N application

1. INTRODUCTION

Nitrous oxide contributes to global warming (GW) by virtue of being 298 times more effective than carbon dioxide (IPCC, 2007). The atmospheric concentration of this greenhouse gas has increased from approximately 275 ppb in pre-industrial times to a present day concentration of 314 ppb (Houghton et al., 1996; IPCC, 2007). Agricultural land is the most important sources of N_2O emissions, contributing approximately 46-52% of the global anthropogenic N_2O flux (Mosier et al., 1998; Kroeze et al., 1999; Olivier et al., 1998). Primary reasons for enhanced N_2O emissions from cultivated soils are increased N inputs by mineral fertilizers, animal wastes and biological N fixation (IPCC, 1997 2007). Other factors which affect N_2O emissions are temperature, moisture, crop type, fertilizer type, soil organic carbon content, soil pH, tillage and soil texture (Dobbie et al., 1999; Stehfest and Bouwman, 2006; IPCC, 2007; Metay et al., 2007).

Increases in surface air temperature due to climate change would be expected to increase evaporation leading to higher levels of atmospheric water vapour and a greater variability in the frequency and extent of rainfall (Kattenberg et al., 1996). Ireland is defined as having a marine west-coast climate (Strahler, 1969) with an average annual temperature of 9 °C, 150–200 days with a rainfall over 1mm, and annual rainfalls of 800–2800 mm (Met Eireann, 2009). The Irish climate will continue to warm, towards the end of this century, temperature will increase by 3-4 ^{o}C particularly in the summer and autumn seasons. The winter will be wetter + (15-25%) and summers will be drier - (11-18%) compared to 1961-2000 values (C4 I, 2008). Such changes in temperature and precipitation would be expected to influence mineralisation and denitrification and consequently N_2O production.The aims of this study were to measure and model N_2O fluxes from Irish arable soils and to investigate the efficacy of reduced tillage, reduced N fertilizer and future climate change on N_2O fluxes and to study the relationship between crop yield and N-induced fluxes of N_2O.

2. MATERIAL AND METHODS

2.1. Experimental Site

Measurements of N_2O flux were carried out for two consecutive growing seasons on spring barley field at the Teagasc Oak Park Research Centre, Carlow, Ireland; April-August 2004 and April - August 2005. The soil is classified as a sandy loam with a pH of 7.4 and a mean organic carbon and nitrogen content at 15 cm of 19.4 and 1.9 g kg^{-1} dry soil respectively. In both seasons the experiment was managed under two different tillage regimes; conventional tillage where inversion ploughing to a depth of 22 cm was carried out in March five weeks prior to planting, and reduced tillage to a depth of 15 cm which was carried out in September of the year before. The experimental design was a complete randomized block design.

2.2. Fertilization Treatments

In 2004 three rates of N-fertilization: control (N_0), 70 (N_1) and 140 (N_2) kg N ha^{-1} were applied once on 27th of April 2004, whereas in 2005 fertilizer was applied in two applications, the first on the 12th of April (control, 53 and 106 kg N ha^{-1}) and the second on the10th of May (control, 26 and 53 kg N ha^{-1}). The total amount of N-fertilizer applied in 2005 was therefore control (N_0), 79 (N_1) and 159 (N_2) kg N ha^{-1}. Fertilizer was applied in the form of calcium ammonium nitrate (CAN).

2.3. Measurement of N_2O Flux

Nitrous oxide fluxes were measured using the methodology of Smith *et al.* (1995). Chambers consisted of three parts: a 52 x 52 x 15 cm high square collar inserted permanently in the soil over which a 50 x 50 x 30 cm high lid with a plastic septum could be sealed in place for gas sample collection. Samples were taken using a 60 ml gas-tight syringe after flushing of the syringe to ensure adequate mixing of air within the chamber. All 60 ml of the sample was then injected into a pre-evacuated 3ml gas-tight vial with a vent needle inserted into the top. Flux was measured using a gas chromatograph (Shimadzu GC 14B, Kyoto, Japan) with electron capture detection.

2.4. Soil Nitrate and Moisture

Twelve soil samples were taken at a depth of 0 - 20 cm on every gas-sampling occasion. In addition, daily precipitation was measured at the Teagasc Research Centre weather station. The concentration of soil nitrate was measured colourimetrically using a Bran and Luebbe AutoAnalyzer (Bran and Luebbe, Norderstedt, Germany), based on the method of Armstrong et al., (1976).

2.5. Grain Yields and Protein Content

Crop grain yield samples representing all treatments and tillage systems were collected from the field by the Teagasc Research Centre team. Average grain yields at 15% moisture were determined for each N fertilizer/ tillage combination.

Protein content was measured for intact grains using a Foss, Infratec 1241 Grain Analyzer.

2.6. DNDC Model and Climate Scenarios

The rainfall driven process-based model DNDC (Li et al., 1992) was used in this study. Measured soil, climate and management data were used for model input. Three climate scenarios were investigated: a measured baseline climate (1978-2007), from a nearby weather station; and two future scenarios (2061-2090; high and low temperature sensitive) from the Hadley Centre Global Climate Model ($HadCM_4$) based on the IPCC AB1 emission scenario and range out the uncertainty (Collins et al. 2006). The CO_2 concentrations used for the simulations were 370 ppm for the baseline and 700ppm for the future scenarios (IPCC, 2007).

2.7. Statistics

Data were analyzed using SPSS, PRISM (GraphPad, San Diego, USA) and Data Desk (Data Description Inc. New York, USA) software. All data was checked for normal distribution and log transformed where appropriate.

3. RESULTS AND DISCUSSION

Throughout the growing season, fluxes of N_2O were low with few high peaks observed only following application of N fertilizer. These high peaks are associated with high uncertainty and depend on many factors e.g. time of measurements, weather, and soil. Changing in these peaks values may change the cumulative flux as peaks represent approximately 90% of the flux. The highest peaks of 56 gN_2O-N ha^{-1} d^{-1} (2004) and 32 gN_2O-N ha^{-1} d^{-1} (2005) recorded from this study were observed 1 day and 9 days after fertilizer application, respectively (Figures 1 and 2). The delay in 2005 most likely due to dry weather during fertilizer application period (McSwiney and Robertson 2005; Wang et al., 2005). Despite the fact that in 2005 the first application of N fertilizer represented 2/3 of the total N applied, highest peak was observed from the second fertilizer application. Here, the greatest total precipitation during the month May (72mm) compared with that of April (39mm) is believed to be responsible for this increase (Wang et al., 2005).

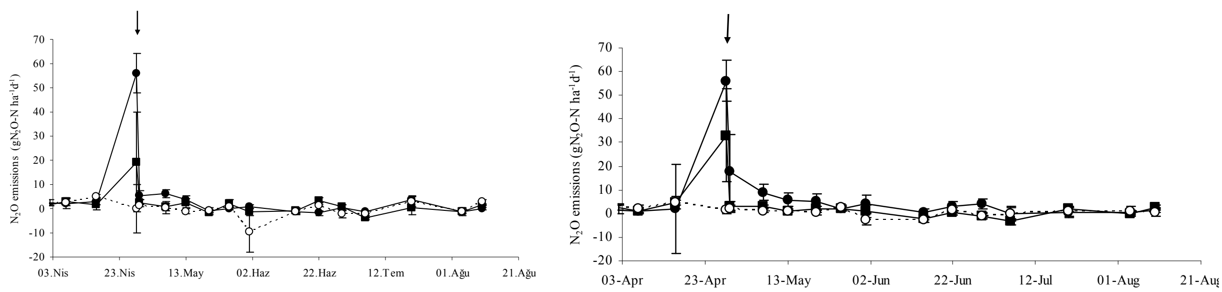

Figure 1. Daily fluxes of N_2O from the conventional (a) and reduced (b) tillage plots measured on a weekly basis in 2004. Symbols indicate fertilizer rate level at which N_2O flux was measured: N2 (●), N1 (■) and N0 (o). Arrows indicate first measurements following fertilizer application. Each point represents the mean ± SE of four measurements

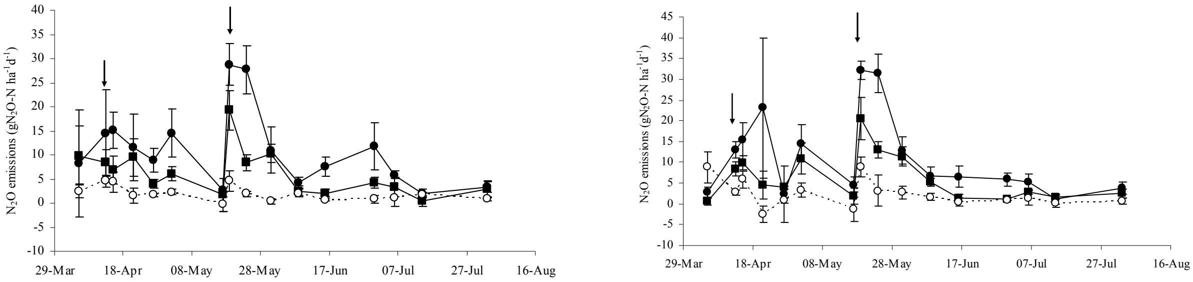

Figure 2. Daily fluxes of N_2O from the conventional (a) and reduced (b) tillage plots measured on a weekly basis in 2005. Symbols indicate fertilizer rate level at which N_2O flux was measured: N2 (●), N1 (■) and N0 (o). Arrows indicate first measurements following fertilizer application. Each point represents the mean ± SE of four measurements

Cumulative fluxes of N_2O recorded in this study (0.26 – 0.98 kg N_2O-N ha^{-1}; Table 1), were comparable with that from winter wheat reported by Smith et al., (1998) but significantly low compared with fluxes reported from other arable soils of similar climate and ecosystems ranging from 1.2 to12 kg N_2O-N ha^{-1} (Ball et al., 1997-*Scotland*; Kaiser et al., 1998-*Germany*; Choudhary et al., 2002-*New Zealand*). However, differences between our experiment soil, crop and applied N fertilizer of these studies are behind these flux differences (Kaiser et al., 1998; Flechard *et al*., 2007).

Adoption of reduced tillage, in the short run, as a means for mitigating N_2O fluxes from the soil would not be successful. This is in contrast to similar studies by Paustian et al., (1997) and Schlesinger, (1999). Initial increases in N_2O flux from non inversion tillage (NIT) have been a consistent observation in the literature (Aulakh *et al*., 1984; Bouwman, 1996; Baggs et al., 2003). This increase may need a period of at least 10 years to return to background levels and 20 years to see any mitigation effects on greenhouse gas emissions in general (Six et al., 2004). However, a long-term N simulation study by Li et al., (2005), found that NIT could increase N_2O fluxes from a maize/ soybean rotation in Iowa, USA offsetting 75% of carbon sequestered. In that study flux increase was related to an increase in soil organic carbon content under NIT.

Availability of mineral N has a direct influence on N_2O production by provision of N for both nitrification and denitrification (Baggs and Blum, 2004). In this study, soil mineral nitrogen in the form of nitrate is one of the main driving factors in the production of N_2O as shown by regression analysis (Bouwman, 1990; Mosier, 1994). Another factor is soil moisture which stimulates denitrification by temporarily reducing the oxygen diffusion into the soil (Dobbie and Smith, 2001) and increases the solubility of organic carbon and nitrate in the soil (Bowden and Bormann, 1986). This co-requirement for soil moisture and soil N for maximum fluxes of N_2O is in agreement with many other studies over a range of different soils and crop systems (McSwiney and Robertson, 2005 - *arable*; Abassi and Adams, 2000; Maddok et al., 2001; Ball et al., 2002 and Maljanen et al., 2002 – *forest and grasslands*).

The emission factors (EF) calculated in this experiment for different fertilizer treatments are range from 0.42 to 0.65% (Table 1). However, measurements in our study covered only the crop growth season, and no post harvest flux was included. Post harvest emissions can significantly contribute to the annual budget (Smith et al., 1998; Syvasalo et al., 2004). Our overall EF for this field is 0.6%. This is approximately 50 and 67% of the default emission factors of 1.25 and 0.9% proposed by the IPCC (Bouwman, 1996; IPCC, 1997; IPCC, 2006), respectively. Literature EF values for cereal crops are extremely variable, ranging from 0.2 to 8% (Eichner, 1990; Kaiser et al., 1998; Smith et al., 1998, Dobbie et al., 1999).

Table 1. Cumulative N_2O-N emitted, grain yields and emission factors for the conventional and reduced tillage plots in 2004/2005

Treatment	Grain yields (t ha^{-1}), cumulative N_2O flux (kg N_2O-N ha^{-1}) and EF (%)					
	Conventional tillage			Reduced tillage		
2004						
140 kg N ha^{-1}	7.73	0.79 ± 0.08	0.63 ± 0.06	7.58	0.98 ± 0.21	0.63 ± 0.2
70 kg N ha^{-1}	6.34	0.26 ± 0.26	0.42 ± 0.41	6.43	0.49 ± 0.28	0.65 ± 0.45
0 k N ha^{-1}	3.41	0.01 ± 0.13	-	3.20	0.09 ± 0.03	-
2005						
159 kg N ha^{-1}	6.55	0.87 ± 0.04	0.61 ± 0.03	6.17	0.94 ± 0.2	0.65 ± 0.14
79 kg N ha^{-1}	5.92	0.39 ± 0.097	0.54 ± 0.13	4.93	0.42 ± 0.02	0.59 ± 0.03
0 k N ha^{-1}	2.91	0.16 ± 0.03	-	2.64	0.13 ± 0.09	-

Each value represents the mean ± SE of four replicate values

Emission factors for Ireland have previously been calculated for some grasslands only e.g Hsieh et al., (2005) for a grassland in Cork (3.4%), and Hyde et al., (2006) for a grassland in Wexford (0.7 to 4.9%). Regional variations in emission factors have yet to be determined for Irish soils and will be dependant upon a variety of factors, namely temperature, moisture and soil type (Bouwman et al., 2002; Flechard et al., 2007). Reducing the fertilizer application rate by 50% has reduced N_2O flux by a similar amount but has had little effect on grain yield (Figure 3).

In contrast, grain quality in terms of protein content was more sensitive to N fertilizer application rate. Here, a Bonferroni post hoc test analysis showed the highest protein content to be associated with the field rate fertilizer treatment (P<0.001). No significant differences in protein content was observed between the zero and half field rate fertilizer treatments (P>0.05). Such observations are common in the literature (Smith and Gyles, 1988; Kindred *et al*., 2008). However, even accepting the significant decrease in protein content on reducing the fertilizer application rate by 50%, in terms of malting quality, the important criterion is that the protein content of the grain should be in the range of about 9.0 - 12.0%. This has still been achieved for the half-field rate fertilizer treatment. These data on grain yield and quality, coupled with the N_2O flux measurements would suggest that a significant reduction in N_2O emissions from the soil would be possible by reducing N fertilizer application in the order of 50% without critically altering grain yield or quality in terms of required protein content.

This suggests that N_2O flux has a threshold response to N fertilization where the amount of N lost to the atmosphere depends on the amount of N taken up by the crop. Exceeding this threshold value results in a higher release of N_2O to the atmosphere (McSwiney and Robertson, 2005). However, applying N fertilizer according to soil N reserves, and matching the time of application to crop uptake, significantly reduces N_2O emissions with no significant difference in crop yield (Wagner-Riddle et al., 2007).

The relationship between observed and modelled data is illustrated in Figure 4. The regression (y = 0.78x - 6.5) accounts for 85% of the variation in the data, but with the simulated values (y) underestimating measured values (x) by 24%.

Modelled fluxes for the high fertilizer inputs agreed with field measured values, giving the smallest relative deviations from field data of -1 and -6%. These deviations increase significantly as fertilizer input is reduced. The largest % deviation, and hence the worst fit was obtained for the zero fertilizer treatments, with relative deviations of -35 to more than 100% calculated. Clearly DNDC is best suited for medium to high N input treatments and does not account for negative flux values that can occur in low to zero N input treatments where the soil may act as a sink for N_2O (Ryden, 1981; Clayton et al., 1997).Similar DNDC results for high and medium N fertilizer inputs have been reported for rice fields by Zheng et al. (1999) (381 kg N ha^{-1}; 8% deviation), for maize fields by Crill et al. (2000) (181 kg N ha^{-1}; 3.5% deviation), for grass by Hsieh et al. (2005) (337 kg Nha^{-1}; 33% deviation) and for barley fields by Flessa et al. (1995) (50 kg N ha^{-1}; 36% deviation). However, these observations are not consistent in the literature. In contrast to our results far better agreements between modelled and measured flux values have been obtained for low to zero N inputs by Terry et al. (Pahokee muck soil; rainy season; 1981), Beheydt et al. (Belgium; sandy loam soil; rainy season; 2007) and Qiu et al. (China; paddy soil; low precipitation; 2009).

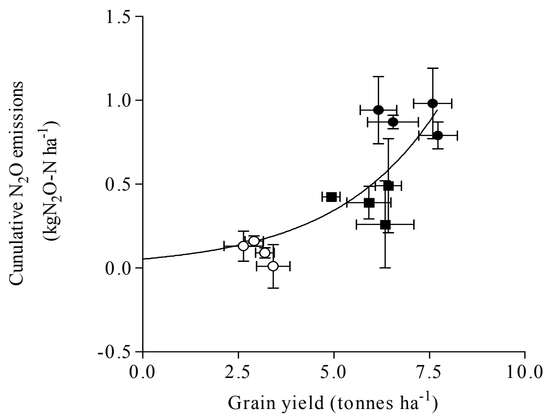

Figure 3. Relationship between the grain yield of spring barley (at 15% moisture) and the cumulative flux of nitrous oxide over the growing season for both 2004 and 2005 combined. Each point represents the mean ± se of 4 values. Symbols indicate fertilizer rate level: N_2 (●), N_1 (■) and N_3 (○). Line indicates curve of best fit where $y = 0.053*e^{0.373x}$, ($r^2 = 0.69$)

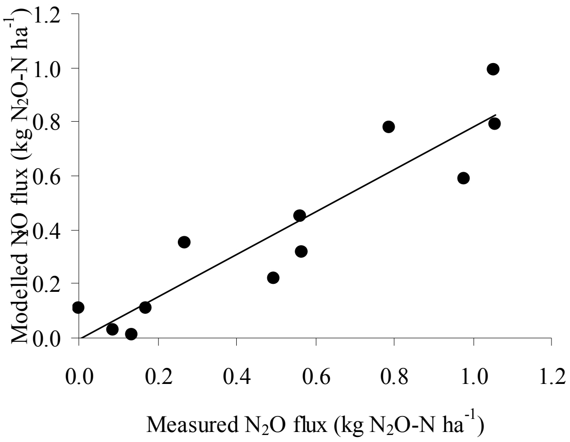

Figure 4. Correlation between the model-simulated and field measured N_2O fluxes for the arable field. y = 0.78x -6.5 (r^2 = 0.85)

The cumulative N_2O fluxes, under future high and low temperature sensitive climate scenarios, for reduced tillage were higher by 11-35% and 14-41% compared with that for conventional tillage respectively. Here, the significant differences (P<0.001) was at the zero applied N (Table 2). The IPCC methodology (IPCC, 1997) accounts for an estimated SOC rise of 10% with conversion from conventional tillage systems to no-till but it does not take into account increases in N_2O emissions (Mosier et al., 1998).

Under climate change, the high temperature sensitive scenario, would produce significantly higher (P<0.001) cumulative nitrous oxide fluxes from both tillage treatments, compared with the baseline fluxes (Table 2). These flux increases ranged from 58 to 85% and from 79 to 88% for conventional and reduced tillage, respectively. However, under the low temperature sensitive scenario, changes in the flux were not significantly different (P>0.05) and ranged from +16% to (-26%) for both tillage treatments. The significant increases in the flux under the high temperature sensitive scenario were attributed to the increasing in minimum and maximum temperature and precipitation compared with baseline. Our study predicted future higher N_2O emissions in long-term (30 years) reduced tillage due to increasing temperature. This may lead to positive feedback and higher global warming (Six et al., 2002). Li et al., (2005) reported that non-inversion tillage could increase N_2O fluxes, due to increased soil organic carbon content, offsetting 75% of carbon sequestered. However, Six et al., (2004) concluded that differences in N_2O fluxes between till and no-till/reduced till change over time, depend on climate and may need approximately 20 years to see any mitigation effects of no-till on greenhouse gas emissions in general.

At the high sensitive scenario, N mineralisation, from both tillage treatments, was significantly high (P<0.001) and increased by 22-27% compared with the baseline. However, these increases were not significantly different (P>0.05) under the low sensitive scenario and ranged from 4 to 11%. Soil characteristics and environmental conditions affects mineralisation (Schoenau and Campbel 1996). In this study, temperature and precipitation are the major factors affecting N mineralisation and consequently N_2O fluxes from soils.

Table 2. Simulated cumulative N_2O fluxes under different N fertilizer levels, tillage systems and climate scenario: baseline, higher temperature sensitive (HTS) and low temperature sensitive (LTS)

Treatment	Cumulative N_2O flux (kg N_2O-N ha^{-1}) and future change compared with baseline climate scenario (%)					
	Conventional tillage			Reduced tillage		
	Baseline	HTS	LTS	Baseline	HTS	LTS
2004						
140 kg N ha^{-1}	5.5a	9.8ab	5.7a	5.9a	11ab	6.5a
70 kg N ha^{-1}	4.9b	8.6ac	4.5b	5.5b	9.9ac	5.3b
0 k N ha^{-1}	4.0c	6.9bc	3.1c	5.0c	9.0abc	4.4c
2005						
159 kg N ha^{-1}	5.7a	10.6ab	6.4a	6.3a	11.8ab	7.3a
79 kg N ha^{-1}	5.0b	8.9ac	4.8b	5.7b	10.2ac	5.6b
0 k N ha^{-1}	4.2c	6.6bc	3.1c	5.0c	8.9abc	4.4c

The increased of N mineralisation with temperature are in agreement with Wennman and Katterer (2006). On the other hand, total denitrifications, at the high temperature sensitive scenario, were significantly higher ($P<0.001$) than the baseline and increased by 49-110% for conventional tillage and by 71-95% for the reduced tillage. However, these increases were not significantly different ($P>0.05$) under low temperature sensitive scenario and mostly decreased due to low temperature. Here, temperature was the major factors that affect denitrification. These increases in total denitrification with temperature are in agreement with Wennman and Katterer (2006) and Abdalla et al., (2009). Under high temperature both soil organic matter decomposition and microbial response to other perturbations, such as fertilization and rainfall, can increase (Antonopoulos1999; Wennman and Katterer 2006). The calculated annual N_2O flux uncertainty, at different N applied fertilizer, were ranged from 74 to 95 % and 71 to 90% for the conventional and reduced tillage, respectively.

4. CONCLUSION

Results of this study show that N_2O emissions from fertilized soils are decisively influenced by N application rate and soil moisture. The overall calculated emission factor is 0.6% of the applied N fertilizer, approximately 50% of the IPCC default EFs of 1.25%, used for estimation of N_2O flux from Irish agriculture. Fluxes and grain yield from conventional and reduced tillage are not significantly different and adoption of reduced tillage as a means of mitigating N_2O emissions from the spring barley field was not successful, at least in the short run. Reducing fertilizer application rate by 50% is an acceptable strategy for low input agriculture in that there was no significant effect on grain yield or quality in terms of required protein content, but seasonal emissions of N_2O were significantly reduced. Nitrous oxide flux has a threshold response to N fertilization where the amount of N lost to the atmosphere depends on the amount of N taken up by the crop. In its present form DNDC is suitable for simulation of C and N dynamics in medium to high N input systems, but less suitable for low input systems, with the accuracy of the prediction being highly dependant on the level of fertilizer application. High fertilizer inputs produce low relative deviations between modelled and measured fluxes (~1-6%) for the arable field under conventional tillage. Prediction of N_2O fluxes from reduced tillage plots however, was poor, with DNDC consistently underestimating measured field values. Here relative deviations ranged from -20 to -93%. Sensitivity analysis also highlighted air temperature as the main determinant of N_2O flux, an increase in mean daily air temperature of 1.5^{o} C resulting in almost 65% increase in the annual cumulative flux. Although, reduced tillage is known with its ability to sequester C in the soil, our study showed significant increase in N_2O flux with climate change due to increasing temperature. The differences in cumulative flux between the two tillage treatments increase with climate change. With increasing temperature, nitrous oxide fluxes from both tillage systems would significantly increase compared with the baseline. At the high sensitive temperature scenario, flux increases were ranged from 58 to 85% and from 79 to 88% for conventional and reduced tillage respectively. However, at the low temperature sensitive scenario, for both tillage systems, the fluxes were increase by up to 16% only, at the high fertilizer, and decreased by up to 26% at low (70-80) and zero kg N fertilizer application rate. By the year 2090, N_2O flux from the Irish arable soils will significantly increase. Elevated temperature and precipitation, due to climate change, can increase N mineralisation and total denitrification and consequently N_2O emissions from soil. The annual flux uncertainties due to simulating different weather variability were ranged from 74 to 95 % and 71 to 90% for the conventional and reduced tillage respectively

5. ACKNOWLEDGEMENT

This work was funded by the EU sixth framework program (contract EVK2-CT2001-00105) and Irish EPA. We are grateful to the Irish National Meteorological Service Research Group (Met Éireann) for providing us with the $HadMC_4$ climate projections and Teagasc-Oak Park for facilitating our field

6. REFERENCES

Abassi, M.K., Adams, W.A., 2000. Gaseous N emissions during simultaneous nitrification - denitrification associated with mineral N fertilisation to a grassland soil under field conditions. Soil Biology and Biochemistry, 32: 1251-1259.

Abdalla, M., Jones, M., Smith, P., Williams, M., 2009. Nitrous oxide fluxes and denitrification sensitivity to temperature in Irish pasture soils. Soil Use and Management, 25: 376-388.

Antonopoulos, A.Z., 1999. Comparison of different models to simulate soil temperature and moisture–effects on nitrogen mineralisation in the soil. Journal of Plant nutrition and Soil Science, 162: 667-675.

Armstrong, F.A.J., Sterns, C.R., Strickland, J.D.H., 1976. The measurement of up welling and subsequent biological processes by means of the Technicon Auto analyzer and associated equipment. Deep Sea Research, 14: 381-389.

Aulakh, M.S., Rennie D.A., Paul, E.A., 1984. The influence of plant residues on denitrification rates on conventional and zero-tilled soils. Soil Science Society of America Journal, 48: 790-794.

Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H., Cadish, G. 2003. Nitrous oxide emissions following application of residues and fertilizer under zero and conventional tillage. Plant and Soil, 254: 361-370.

Baggs, E.M. Blum, H., 2004. CH_4 oxidation and emissions of CH_4 and N_2O from Lolium perenne swards under elevated atmospheric CO_2. Soil Biology and Biochemistry, 36: 713-723.

Ball, B.C., Horgan, G.W., Clayton, H., Parker, J.P., 1997. Spatial variability of nitrous oxide fluxes and controlling

soil and topographic properties. Journal of Environmental Quality, 26: 1399-1409.
Ball, B.C., McTaggart, I.P., Watson, C.A., 2002. Influence of organic ley-arable management and afforestation in sandy loam to clay loam soils on fluxes of N_2O and CH_4 in Scotland. Agriculture, Ecosystems and Environment, 90: 305-317.
Beheydt, D., Boeckx, P., Sleutel, S., Li, C., Van Cleemput, O., 2007. Validation of DNDC for 22 long-term N_2O field emission measurements. Atmospheric Environment, 41: 6196-6211.
Bowden, W.B., Bormann, F, H., 1986. Transport and loss of nitrous oxide in soil water after forest clear cutting. Science, 233: 867-869.
Bouwman, A.F.,1990. Exchange of greenhouse gas between terrestrial ecosystems and atmosphere. In: A.F. Bouwman (Ed.). Soil and the Greenhouse Effects. Wiley, Chichester, UK, pp. 61-127.
Bouwman, A.F., 1996. Direct emissions of nitrous oxide from agricultural soils. Nutrient Cycling in Agro-ecosystems, 46: 53-70.
Bouwman, A.F., Bouwmans, L.J.M., Batjes, N.H., 2002. Modelling global annual N_2O and NO emissions from fertilized fields. Global Biogeochemical Cycles, 16: 1080.
C4I, 2008. Community Climate Change Consortium For Ireland. Ireland in a Warmer World. Scientific Predictions of the Irish Climate in the Twenty-first century. Final Report. Access at: http://www.c4i.ie/docs/IrelandinaWarmerWorld.pdf.
Choudhary, M.A., Akramkhanov, A., Saggar, S., 2002. Nitrous oxide emissions from a New Zealand cropped soil: tillage effects, spatial and seasonal variability. Agriculture, Ecosystems and Environment, 93: 33-43.
Clayton, H., McTaggart, I.P., Parker, J., Swan, L., Smith, K.A., 1997. Nitrous oxide emissions from fertilized grassland: a 2 years study of the effect of N fertilizer form and environmental conditions. Biology and Fertility of Soils, 25: 252-260.
Collins, M., Booth, B.B.B., Harris, G.R., 2006. Towards quantifying uncertainty in transient climate change. Climate Dyna, 27: 127-147.
Crill, P., Keller, M., Weitz, A., Grauel, B., Veldkamp, E., 2000. Intensive field measurements of nitrous oxide emissions from a tropical agricultural soil. Global Biogeochemical Cycles, 14: 85-96.
Dobbie, K. E., McTaggart, I.P., Smith K. A., 1999. Nitrous oxide emissions from intensive agricultural systems: variations between crops and seasons; key driving variables; and mean emission factors. Journal of Geophysical Research 104, 26891-26899. Eaton, I.J. and Patriquin, D.J., 1989. Denitrification in low bush blue berry soils. Canadian Journal of Soil Science, 69: 303-312.
Dobbie, K. E. Smith K. A., 2001. The effects of temperature, water filled pore space and land use on N_2O emissions from imperfectly drained gleysol. European Journal of Soil Science, 52: 667-673.
Eichner, M.J., 1990. Nitrous oxide emissions from fertilized soils: summary of available data. Journal of Environmental Quality, 19: 272-280.
Flechard, C., Ambus, P., Skiba, U., Rees, R.M., Hensen, A., Van den Pol, A., Soussana, J.F., Jones, M., Clifton-Brwon, J., Raschi, A., Horvath, L., Van Amstel, A.,Neftel, A., Jocher, M., Ammann, C., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C., Campbell, C., Nemitz, E., Hargreaves, K.J., Levy, P., Ball, B., Jones, S., Van de Bulk, W.C.M., Groot, T., Blom, M., Gunnink, H., Kasper, G., Allard, V., Cellier, P., Laville, P., Henault, C., Bizouard, F., Jolivot, D., Abdalla, M., Williams, M., Baronti, S., Berretti, F., Grosz, B., Dominques, R., 2007. Effects of climate and management intensity on nitrous oxide emissions in grassland systems across. Europe. Agriculture, Ecosystems and Environment, 121: 135-152.
Flessa, H., Dorsh, P., Beese, F., 1995. Seasonal variation of N_2O and CH_4 fluxes in differently managed arable soils in southern Germany. Journal of Geophysical Research, 100: 23115-23124.
Hsieh, C.I., Leahy, P., Kiely, G., Li, C., 2005. The effect of future climate perturbations on N_2O emissions from fertilized humid grassland. Nutrient Cycling in Agro-ecosystems, 73: 15-23.
Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), 1996. Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, NewYork, USA, p. 572.
Hyde, B.P., Hawkins, M.J., Ryan, M., Carton, O.T., 2006. Nitrous oxide emissions from a fertilized grazed grassland in Ireland. International Congress Series, 1293: 351-354.
IPCC, 1997. Revised 1996 IPCC guidelines for national greenhouse gas inventories. IPCC/OECD/IEA, IPCC, Geneva, Switzerland.
IPCC, 2006. 2006 IPCC Guidelines for National Gas Inventories. Prepared by the National Greenhouse gas Inventories Programme Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES. Japan.
IPCC, 2007. Changes in atmospheric constituents and in radiative forcing. Cambridge University Press, UK and New York USA.
Kaiser, E.A., Kohrs, K., Kucke, M., Schnug, E., Heinemeyer, O., Munch, J.C., 1998. Nitrous oxide release from arable soil: Importance of fertilization, crops and temporal variation. Soil Biology and Biochemistry, 30: 1553-1563.
Kattenberg, A.F., Giorgi, H., Grassl, G. A., Meehl, J. F. B., Mitchell, R J., Stouffer T., Tokioka, A. J., Weaver Wigley, T. M.L., 1996. Climate models - projections of future climate, in Climate Change 1995. In: The Science of Climate Change, (Eds) Houghton J T, Filho L G M, Callander B A, Harris N, Kattenberg, A, Maskell K. Cambridge University Press, Cambridge, UK, pp 285-357.
Kindred, R.R., Verhoeven, T.M.O., Weightman, R.M., Swanston, J.S., Agu, R.C., Brosnan, J.M., Sylvester-Bradley, R., 2008. Effect of variety and fertilizer nitrogen on alcohol yield, grain yield, starch and protein content, and protein composition of winter wheat. Journal of Cereal Science, 48: 46-57.
Kroeze, C., Mosier, A., Bouwman, L., 1999. Closing the global N_2O budget. A retrospective analysis 1500-1994. Global Biochemical Cycle, 12: 1-8.
Li, C., Frolking, S., Frolking, T.A., 1992. A model of nitrous oxide evolution from soil driven by rainfall events.1. Model structure and sensitivity. Geophysical Research, 97: 9759-9776.
Li, C., Frolking, S., Butterbach-Bahl, K., 2005. Carbon sequestration in arable soils is likely to increase nitrous

oxide emissions, offsetting reductions in climate radiative forcing. Climate Change, 72 : 321-338.

Maddock, J.E.L., Dos Santos, M.B.P., Prata, K.R., 2001. Nitrous oxide emission from soil of the Mata Atlantica, Rio De Janeiro state, Brazil. Geophysical Research Atmosphere, 106: 23055-23060.

Maljanen, M., Martikainen, P.J., Aaltonen, H., 2002. Short term variation in fluxes of carbon dioxide, nitrous oxide and methane in cultivated and forested organic boreal soils. Soil Biology and Biochemistry, 34: 577-584.

McSwiney, C.P., Robertson, G.P., 2005. Non-linear response of N_2O flux to incremental fertilizer addition in a continuous maize (Zea mays L.) cropping system. Global Change Biology, 11: 1712-1719.

Metay, A., Oliver, R., Scopel, E., Douzet, J.M., Alves Moreira, J.A., Maraux, F., Feigl, B.J., Feller, C., 2007. N_2O and CH_4 emissions from soils under conventional and no-till management practices in Goiânia (Cerrados, Brazil). Geoderma, 141: 78-88.

Met Eireann, 2009. Annual Report, 2009. Access at: www.met.ie.

Mosier, A.R., Klemedtsson, L., 1994. Measuring denitrification in the field. In: Methods of soil analysis. Part 2. Microbiological and Biochemical Properties (R.W. Weaver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. tabatabai and A. Wollum, (eds.), pp. 1047-1065. Soil Science Society of America Journal, Madison.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput, O., Abrahamsen, G., Bouwman, L., Bockman, O., Drange, H., Frolking, S., Howarth, R., Smith, K., Bleken, M.A., 1998. Closing the global N_2O budget, nitrous oxide emissions through the agricultural nitrogen cycle. OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology. Nutrient Cycling in Agroecosystems, 52: 225-248.

Olivier, J.G.J., Bouwman, A.F., Van Der hoek, K.W., Berdowski, J.J.M., 1998. Global air emission inventories for anthropogenic sources of N_x, NH_3 and N_2O in 1990. Environmental Pollution, 102: 135-148.

Paustian, K., Andren, O., Janzen, H.H., 1997. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use and Management, 13: 230-244.

Qiu, J.J., Li, C., Wang, L., Tang, H., Li, H., Van Ranst, E., 2009. Modeling impacts of carbon sequestration on net greenhouse gas emissions from agricultural soil in China. Global Biogeochemical Cycle, 23: GB1007.

Ryden, J.C., 1981. N_2O exchange between a grassland soil and the atmosphere. Nature, 292: 235-237.

Schlesinger, W.H., 1999. Carbon sequestration in soils. Science, 284: 2095.

Schoenau, J.J., Campbell, C.A., 1996. Impact of crop residues on nutrient availability in conservation tillage systems. Canadian Journal of Plant Science, 76: 621-626.

Six, J., Feller, C., Denef, K., Ogle, S.M., De Moraes Sa, J.C., Albrecht, A., 2002.Soil organic matter, biota and aggregation in temperate and tropical soils-effects of no-tillage. Agronomy, 22: 755-775.

Six, J., Ogle, S., Breidt, F.J., Contant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Global Change Biology, 10: 155-160.

Smith, K.A., Clayton, H., McTaggart, I.P., 1995. The measurement of nitrous oxide emissions from soil by using chambers. Philosophical Transactions of the Royal Society of London, Series A 351: 327-337.

Smith, C.J. and Gyles, O.A., 1988. Fertilizer N balance on spring irrigated malting barley. Nutrient Cycling in Agroecosystems, 18: 3-12.

Smith, K.A., McTaggart, I.P., Dobbie, K.E., Konen, F., 1998. Emissions of N_2O from Scottish agricultural soils, as a function of fertilizer N. Nutrient cycling in Agroecosystems, 52: 123-130.

Stehfest, E., and Bouwman, L., 2006. N_2O and No emissions from agricultural fields and soils under natural vegetation: summarizing available measurements data and modelling of global annual emissions. Nutrient Cycling in agro-ecosystem, 74: 207-228.

Strahler, A.N., 1969. Physical geography (3rd ed) New York. Jones CA, Ritchie.

JT, Kiniry JR, Godwin DC, Otter-Nacke SI (1984). The CERES wheat and maize model: Proceeding International symposium on minimum datasets for Agro-technology Transfer. ICRASET, Pantancheru (India), 95-100.

Syväsalo, E., Regina, K., Pihlatie, M., Esala, M., 2004. Emissions of nitrous oxide from boreal agricultural clay and loamy sand soils. Nutrient Cycling in Agroecosystems, 69: 155-165.

Terry, R.E., Tate, R.L.T., III, Duxbury, J.M. 1981. The effect of flooding on nitrous oxide emissions from and organic soil. Soil Science, 132: 228-232.

Wagner-Riddle, C., Furon, A., McLaughlin, N., Lee, I., Barbeau, J., Jayasundara.

S., Parkin, G., Von Bertoldi, P., Warland, J., 2007. Intensive measurements of nitrous oxide emissions from a corn-soybean-wheat rotation under two contrasting management systems over 5 years. Global change Biology, 13: 1722-1736.

Wang, Y., Xue, M., Zheng, X., Ji, B., Du, R., Wang, Y., 2005. Effects of environmental factors on N_2O emission from and CH_4 uptake by the typical grasslands in the Inner Mongolia. Chemosphere, 58: 205-215.

Wennman, P., Katterer, T., 2006. Effects of moisture and temperature on carbon and nitrogen mineralisation in mine tailing mixed with sewage sludge. Journal of Environmental Quality, 35: 1135-1141.

Zheng, X.H., Wang, M.X., Wang, Y.S., Shen, R.X., Li, J., Heyer, J., Kögge, M.,Papen H., Jin, J.S., Li, L.T., 1999. Characters of greenhouse gas (N_2O, NO, CH_4) emissions from croplands of Southeast China. World Resource Review, 11: 229-246.