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The effect of renovation of long-term temperate grassland on N_2O emissions and N leaching from contrasting soils.

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Abstract

Renovation of long-term grassland is associated with a peak in soil organic N mineralisation which, coupled with diminished plant N uptake can lead to large gaseous and leaching N losses. This study reports on the effect of ploughing and subsequent N fertilisation on the N_2O emissions and DON/ NO_3^- leaching, and evaluates the impact of ploughing technique on the magnitude and profile of N losses. This study was carried out on isolated grassland lysimeters of three Irish soils representing contrasting drainage properties (well-drained Clonakilty, moderately-drained Elton and poorly-drained Rathangan). Lysimeters were manually ploughed simulating conventional (CT) and minimum tillage (MT) as two treatments. Renovation of grassland increased N_2O flux to a maximum of 0.9 kg N_2O-N ha^{-1} from poorly-drained soil over four days after treatment. Although there was no difference between CT and MT in the post-ploughing period, the treatment influenced subsequent N_2O after fertiliser applications. Fertilisation remained the major driver of N losses therefore reducing fertilisation rate post planting to account for N mineralised through grassland renovation could reduce the losses in medium to longer term. Leaching was a significant loss pathway, with the cumulative drainage volume and N leached highly influenced by soil type. Overall, the total N losses (N_2O + N leached) were lowest from poorly and moderately

draining soil and highest for the well draining soil, reflecting the dominance of leaching on total N losses and the paramount importance of soil properties.

1. Introduction

Managed grasslands require routine renovation every five to ten years due to sward deterioration with age (Necpalova et al., 2013). In Ireland however, grasslands are reseeded on average every 30 years (Humphreys & Casey, 2002) with a substantial associated risk of losing large amounts of accumulated soil organic matter (SOM) (Velthof et al., 2010). The common practice is ploughing followed by fertilisation, both of which can lead to substantial losses of reactive nitrogen (N). These losses occur due to both the incorporation of plants residues and the disruption of soil aggregates which exposes protected SOM to decomposition (Velthof et al. 2010). Losses of reactive N include nitrous oxide (N_2O) and leached nitrogen principally in nitrate (NO_3-N) form, and dissolved organic nitrogen (DON) (Velthof et al. 2010). Nitrogen losses due to denitrification as either N_2 or N_2O predominantly occur on heavier soils, due to lower soil redox potentials, while leaching can play a more significant role in losses following ploughing and fertilisation in light structured, well drained soils (Sogbedji et al., 2000; Dennis et al., 2012). While ploughing can cause significant N losses, the extent of these effects remains unclear (Kong *et al.*, 2009). Even if grassland is immediately reseeded, there is negligible plant N uptake for a several weeks following ploughing, and mineralized N is vulnerable to loss via N_2O or leaching during this period (Necpalova et al., 2013). For the same reason nitrogen fertiliser applied shortly after ploughing is also susceptible to loss.

Intensively managed grasslands in temperate climates are hotspots of reactive N emissions due to high fertilisation rates, high rainfall, and compaction (Sutton et al., 2011). Between 0.04 and 21.21 kg N_2O-N is produced annually from agricultural soils in Europe (Rees et al., 2013), agricultural management practices being the largest driver of losses. Similarly, 10-

30% of N in pastoral systems is leached and can result in eutrophication upon entering water bodies, posing a risk to human health (Jahangir et al., 2013; Stark and Richards, 2008). Various conservation tillage practices such as reduced tillage and no-till have been used in both arable crops and grassland renovation, primarily in order to improve yields and mitigate soil organic matter loss (Lal et al., 1999; West and Marland, 2002). However, in the wet temperate climate of Ireland, only a small area of arable land, and no grassland, is under conservation tillage. Possible reasons are that conservation tillage, such as reduced or no-till, is not suitable for crop establishment in a temperate climate as it may lead to increased grass weed populations and topsoil compaction (Maede & Mullins, 2005; Forristal & Murphy, 2009). In soils with high clay content under cool and wet weather conditions reduced tillage stimulated N_2O emissions (Ball et al. 2008, Rochette et al. 2008). MacDonald et al. (2011) also found that in wet weather conditions fallow soils emitted twice the amount of N_2O compared to conventional tillage. There are conflicting reports on the effect of tillage method on N leaching. Some authors reported a reduction in N leaching losses in arable crops (Dinnes et al., 2002; Syswerda et al., 2012) while others did not see this effect in tillage soils in Ireland (Hooker et al., 2008; Premrov et al., 1014). However this might not be true for permanent grassland and the effect of tillage method may also depend on soil type (Hansen et al., 1997) as well as climatic conditions.

Fertilisation remains one of the major N loss risks in managed grasslands (Bouwman et al., 2002; Skiba et al., 2012). Application of synthetic fertiliser introduces available N source which can be taken up by plant or quickly lost through gaseous or leaching losses (Smith et al., 1997; Gu et al., 2009). However, most studies focus on fertilisation of grassland with plant cover present (Smith et al., 1998; Ruser et al., 2006; Flechard et al., 2007) and little is known of the fate of fertiliser applied following ploughing of permanent grassland.

A limited body of research is available on the effects of grassland renovation on N losses. Studies of Velthof et al. (2010) and Necpalova et al. (2013) focused on various aspects of this issue with Velthof et al. (2010) particularly focussing on the impact of timing of ploughing and variable fertilisation rates, while Necpalova et al. (2013) assessed full system N loss. However, both studies exhibited experimental weaknesses such as using soil samples as indicator of leaching instead of direct measurements (Velthof et al., 2010) or using only one soil type and delaying the start of measurements until a few months after reseeding (Necpalova et al., 2013).

In the light of these conflicting results and limited evidence from permanent grassland experiments in temperate climates, this study was set up to evaluate environmental consequences and to assess the fate and quantify reactive N losses upon renovation and fertilisation of long-term temperate grassland with an emphasis on (1) N_2O emissions and (2) N (DON-N/ NO_3-N) leaching to shallow groundwater.

2. Materials and methods

2.1 Site characteristics

The experiment was carried out at a field lysimeter facility at Teagasc, Johnstown Castle Environmental Research Centre in Wexford, Ireland (6° 30’ W/ 52° 17” N) between May 2009 and July 2010. Eighteen lysimeters (0.8 m diameter, 1 m deep) excavated as intact grass monoliths in 2003, were used. Lysimeters represented three Irish soils of various drainage properties; a poorly draining Rathangan gleysol (WRB: Luvic Stagnosol (Eutric, Siltic)), a moderately draining Elton Brown Earth (WRB: Cutanic Luvisol (Siltic)), and well-draining Clonakilty brown podzol (WRB: Haplic Podzol (Anthric)) (IUSS Working Group WRB, 2006). Soil properties were analysed at the time of collection in 2003. Available N and soil bulk density at the top 0-5cm were determined prior to treatment application following methods of Hoekstra et al. (2010) and the British Standard (2006), respectively. These soil properties are shown in Table 1. Plant cover consisted mostly of perennial ryegrass (*Lolium perenne)*. Between 2004 and 2008 the lysimeters were used to simulate typical Irish grazed grassland activities and received annual fertiliser amounts of 150-300 kg N ha^{-1} yr^{-1} (Dennis et al., 2012). The experimental site lies in a mild north Atlantic temperate climate. Rainfall and air temperature were recorded at the meteorological station adjacent to the experimental site.

2.2 Treatments

Lysimeters were laid out in a randomised block design. Treatments were applied to compliment this design. Three replicates of treatments were used on each soil type. During the experiment, lysimeters were cultivated in order to simulate two ploughing techniques, and were subsequently fertilised and reseeded with perennial ryegrass (*Lolium perenne*, variety Portstewart) at a rate of 60 kg ha-^{1}. Soil cultivation was with conventional inversion tillage (CT) to a depth of approximately 30 cm applied manually with spade on 16th June and minimum (conservational) tillage (MT) to a depth of approximately 10 cm applied manually with a rake on 18th June. Fertiliser was applied to all lysimeters on four occasions during the study (Table 2) at a total rate of 130 kg N ha^{-1}. Three replicates of Rathangan control from a nearby experiment were used for N_2O comparison purposes. Leaching losses were compared to control results of Dennis et al. (2012) of the experiment conducted on the same lysimeters in the previous year.

2.3 N_2O sampling and analysis

Gas samples were collected on 16 occasions over 17 weeks of the experimental period between 25th May and 17th September 2009. Samples were collected once a week for three consecutive weeks prior to ploughing to determine background N_2O emissions. Following ploughing on 16th and 18th June for conventional and minimum tillage respectively, gas sampling was performed daily for the first five days, and then weekly to bi-monthly. Samples were collected using the static chamber method (Mosier, 1989; de Klein and Harvey, 2012), 218 L polyvinyl chloride (PVC) lids painted reflective white fully enclosed the lysimeters fitting into the edges filled with water to ensure the seal of the chamber. Twenty ml samples were drawn 20 and 60 minutes after chamber closure through a rubber septum (Becton Dickinson, UK) using a 20 mL polypropylene syringe (BD Plastipak, Becton Dickinson, UK) with a hypodermic needle (BD Microlance 3, Becton Dickinson, UK) and injected into pre-evacuated (to -1000mbar) 7 mL screw-cap septum glass vials (Labco, UK). Nitrous oxide concentrations were analysed using a gas chromatograph (GC) (Varian CP 3800 GC, Varian, USA) fitted with a ^{63}Ni electron capture detector (ECD) with high purity helium as a carrier gas. Samples were returned to ambient pressure prior to analysis and fed into the system by a Combi-Pal automatic sampler (CTC Analysis, Switzerland). The temperatures of column, injector and detector were 60, 60 and 300 °C, respectively. The GC was calibrated daily and a reference gas standard of known concentration was analysed every eight unknown samples. Areas under N_2O peaks were integrated using Star Chromatography Workstation (Varian, USA). Hourly N_2O emissions were calculated based on the rate of change in N_2O concentration within the chamber during the measurement period and taking into account air temperature, atmospheric pressure, and the ratio of surface area to chamber volume. Hourly N_2O flux was used to calculate daily emissions (Blackmer et al. 1982; de Klein et al. 2003). Cumulative emissions were calculated by integrating the calculated daily fluxes and linear interpolation between measurement points (de Klein and Harvey, 2012). Due to the temporal pattern over the experimental period, N_2O flux has been divided into three separate periods; pre-treatment, post-ploughing and post-fertiliser periods.

2.4 Leachate collection and analysis

Lysimeters were gravity drained, with leachate piped from the lysimeter base to 20 L low density polyethylene (LDPE) containers. Leachate was sampled with weekly to monthly frequency as required by the quantity of rainfall between the 18th May 2009 and 17th July 2010. Leachate volume was recorded and sub-samples collected on each sampling occasion and sub-sampled. Leachate was analysed for total nitrogen (TN) on Shimadzu Total Organic Carbon Analyser using combustion oxidation method with chemiluminescence detection (Ammann *et al*., 2000) and inorganic N (NO_3-N, NH_4-N and NO_2-N) were analysed colorimetrically using a KON E Aquakem Analyser (600A Module; Labmedics Analytical Solutions). Dissolved organic nitrogen (DON) was calculated by subtraction of mineral N fraction from total N.

2.5 Statistical analyses

Statistical analysis was performed using SAS 9.3 (© 2002-201 0, SAS Institute Inc., Cary, NC, USA). All data were tested for normal Gaussian distribution and log transformed where necessary for statistical analysis and back transformed thereafter. A mixed linear model procedure of SAS (PROC GL IMM IX) followed by a Tukey’ s multiple comparison test was used to determine differences between treatments. The model tested the effects of soil, treatment and their interaction on cumulative N_2O-N losses, cumulative leached N losses, and combined gaseous and leached losses. Additionally, the effects of soil, treatment, experimental period, and their interactions on N_2O following ploughing and fertiliser applications, were tested.

3. Results

3.1 Environmental variables

During the N_2O sampling experimental period mean daily temperatures ranged between a minimum of 8.3°C to a maximum of 18.6°C, with a mean temperature for the experimental period of 14.5°C, which was 0.8°C higher than the 30 year average for the comparison months (Fig. 1). Cumulative rainfall recorded during the N_2O sampling experimental period was 526 mm and this was on average 73% higher than the 30 year average for the comparison months (Fig. 1). Out of 116 days of the experiment rainfall was recorded in 74 cases and there were 22 days with rainfall over 10mm.

The experimental period for leaching collection lasted 428 days. Mean daily temperatures for this period ranged between -1.2°C and 18.6°C, with a mean temperature of 10.5°C compared to 11.2 °C 30 year average for the comparison period (Fig. 1). Cumulative rainfall for the leaching collection period was 1584 mm compared to 1010 mm 30 year average for the comparison period (Fig. 1).

3.2 N_2O fluxes

Ploughing and fertilisations of lysimeter soils produced peak N_2O emissions. Separate peaks could be distinguished post-treatment (Fig. 2 a & b), therefore N_2O from separate 'ploughing' and 'fertilising' periods was explored as well as the total post-treatment N_2O loss. Prior to ploughing N_2O emissions were consistently low with mean daily values between 0.0, 1.6, and 1.8 g N_2O-N $ha^{-1}d^{-1}$ for Clonakilty, Elton, and Rathangan soils, respectively (Fig. 2 a & b), there were no significant differences in emissions between soils. Nearby Rathangan control ranged between -2.1 and 7.6 g N_2O-N $ha^{-1}d^{-1}$, and averaged 2.4 g N_2O-N $ha^{-1}d^{-1}$ throughout the experimental period (Fig. 2 a & b).

Nitrous oxide increased immediately following ploughing with maximum fluxes recorded for the first 24 hours post-ploughing. Maximum N_2O values ranged between 58.4 and 364.5 g N_2O-N $ha^{-1}d^{-1}$ for MT Elton, and CT Rathangan, respectively (Fig. 2 a & b). Ploughing accounted for between 7%, 8%, and 11% of cumulative emissions post-treatment from Clonakilty, Elton, and Rathangan soils, respectively, in the MT treatment, whereas in the CT treatment emissions ranged 15%, 23%, and 28% from Clonakilty, Elton, and Rathangan soil, respectively. Fertiliser applications resulted in another peak in N_2O flux which persisted for approximately 50 days and produced the majority of the N_2O flux during the experimental period (Fig. 2 a & b). Largest daily fluxes ranged between 58.0 and 261.8 g N_2O-N ha^{-1} from CT Elton and MT Elton, respectively. The fertilisation period contributed 92%, 93%, and 89% of post-treatment emission for Clonakilty, Elton, and Rathangan, respectively, in the MT treatment, and 85%, 77%, and 72% for Clonakilty, Elton, and Rathangan, respectively, in the CT treatment. Soil had a significant effect on cumulative N_2O emissions following ploughing and fertilising ($P<0.05$), with emissions being significantly higher from Rathangan > Elton = Clonakilty (Table 3 & 4). Significant interaction for period x treatment was detected (Table 3). There was no difference between MT and CT N_2O emissions during the ploughing, however N_2O from fertilising MT and CT was significantly higher than from ploughing CT and MT, and there was also a significant difference between fertilising CT and fertilising MT. Subsequently, N_2O emissions followed a pattern: fertilising MT> fertilising CT> ploughing CT = ploughing MT (Table 4).

Overall, the cumulative post-treatment (ploughing and fertilisation periods combined) N_2O emission ranged between 2.4 and 9.5 kg N_2O-N ha^{-1} from CT Elton and MT Clonakilty, respectively. There was a significant treatment effect ($P<0.001$) (Table 6). In comparison, nearby Rathangan control yielded 0.25 kg N_2O-N ha_{-1}.

3.3 N leaching

The response of N leachate to ploughing and fertilisation was delayed by approximately a month, which concurred with a previous study on the same soils (Dennis *et al*., 2012). It was not possible to apportion N leached between ploughing and fertiliser applications therefore leaching was integrated over the whole experimental period. Here, results of drainage volume, TN, NO_3-N, NH_4-N and DON are presented (Table 5). Soil had a significant effect on all of the leached N losses (P<0.01 to P<0.001) except for DON, whilst treatment was not significant. Rathangan was significantly different from Elton and Clonakilty with lower drainage volume, lower NO_3-N, DON, and TN, and Rathangan and Elton also had lower NH_4-N.Drainage volume ranged between 105 mm and 238 mm from Rathangan CT and Clonakilty CT, respectively. Between 26% and 60% of the rainfall from the experimental period was recovered in leachate. Cumulative TN losses varied between 2.5 kg N ha^{-1} for Rathangan CT and 22.9 kg N ha^{-1} for Clonakilty CT (Table 5). Majority of the N recovered in leachate was in the form of NO_3-N, practically all of which was NO_3-N where between 1.6 kg N ha^{-1} 22.1 kg N ha^{-1} was recorded for Rathangan CT and Clonakilty CT, respectively. Dissolved organic nitrogen was the second highest N fraction in leaching, ranging between 0.3 and 2.5 kg N ha^{-1} for Elton MT and Clonakilty MT, respectively. Ammonium contributed the smallest fraction of the TN ranging between 0.06 and 0.21 kg N ha^{-1} for Elton MT and Clonakilty CT, respectively.

3.4 Total N losses

Total losses of combined N_2O and N leaching varied between 6.7 kg N ha^{-1} for Rathangan CT and 26.3 kg N ha^{-1} for Clonakilty CT (P<0.05) (Table 6). Soil type had a significant effect on overall N loss (P<0.05), with the poorly draining (Rathangan) soil exhibited lower total N losses compared with the other two soils (P<0.05). Overall, the N losses followed the pattern of Rathangan < Elton = Clonakilty. Treatment had no significant effect on total N loss.

4. Discussion

4.1 Nitrous oxide losses post-ploughing

The ploughing and fertilisation of long-term temperate grassland during renovation was a source of large reactive N losses via both gaseous emissions and leaching. Tillage has been reported to disrupt soil structure leading to release of gas trapped in soil pore space (Ball *et al*., 1999; Heincke and Kaupenjohann, 1999). Maximum daily fluxes reported in this study were comparable with the lower end of the range of N_2O following ploughing of managed grasslands reported in previous studies which range between 240 and 1200 g N_2O-N $ha^{-1}d^{-1}$ (Davies et al., 2001; Dobbie & Smith, 2003; Ball et al., 2007; Mori and Hojito, 2007; Necpalova et al., 2013). Poorly draining soils exhibited high fluxes of N_2O with 0.9 kg N_2ON ha^{-1} emitted within four days of ploughing, as well as the highest share of ploughing-derived N_2O. Pinto et al. (2004) found N_2O of 0.3 kg N_2O-N ha^{-1} over five days following ploughing of perennial grassland on sandy clay loam soil which is comparable with 0.4 and 0.7 kg N_2O-N ha^{-1} from moderately and well draining soils respectively, in this experiment. Poor soil drainage and a heavy clay texture can impede N_2O diffusivity, releasing large amounts of N_2O upon ploughing (Heincke and Kaupenjohann, 1999). Clay content is also related to the quantity and quality of soil aggregates protecting SOM (FAO, 2005). However, here N_2O exhibited only a weak correlation with soil clay content, possibly due to high variability in N_2O fluxes.

Previous studies found higher N_2O from minimum versus no-till (Ball et al., 1999; Velthof et al., 2010; MacDonald et al., 2011), and higher N_2O from minimum versus standard tillage (Rochette et al., 2008). These studies attributed higher emissions in no-till and min-till to greater soil compaction, reduced gas diffusivity and less aerobic conditions, however in this study there was no significant difference between CT and MT in the post-ploughing measurement period. Soil and period x treatment interaction were the main drivers of N_2O emissions after ploughing and fertiliser applications. Although there was no difference between CT and MT in the ploughing period, the treatment influenced subsequent N_2O after fertiliser applications.

Minimum tillage is known to enhance soil water-holding capacity, resulting in higher water-filled pore space and less aerobic soil conditions (Velthof et al., 2010). This effect, although the correlation was weak, was observed here (Fig. 3). It is believed that higher WFPS was responsible for the larger N_2O associated with MT soils in the fertiliser period, as soil conditions favoured loss.

4.2 Nitrous oxide losses post-fertilisation

Whilst N_2O flux following ploughing was believed to be mostly due to degassing, N_2O linked to fertiliser applications was most likely to be caused by microbial activity acting on the new supply of available N and mineralisation of exposed organic matter. Temporal pattern of N_2O exhibited high and short-lived peaks following ploughing, whereas post-fertiliser flux remained enhanced over a long period, firstly due to split application and also environmental conditions favouring loss. Soil and period x treatment interaction were the sources of variation in N_2O in the two separate measurement periods. However treatment was significant on cumulative N_2O for the whole post-treatment period. Dennis (2009) found very low N_2O emissions from control and fertiliser treatment measured from the same lysimeters in 2006, whereas large losses in this experiment are most likely due to soil disturbance through ploughing.

Fertilisation immediately post-cultivation remained the major driver of N losses during land preparation. Long-term temperate grasslands accumulate high levels of SOM which become mineralized upon renovation. Mineralizable N is routinely ignored in intensive agricultural systems (Griffin, 2008) however this pathway is a valuable source of N available for plant uptake and when included in fertiliser planning could lead to an improved N fertiliser use efficiency and reduced environmental stress (McDonald et al., 2014). Therefore reducing fertilisation rate post planting to account for N mineralised through grassland renovation could reduce the losses.

4.3 Leaching losses post-ploughing and fertilisation

Leaching was a significant loss pathway, with NO_3-N the main leached fraction and the cumulative drainage volume and N leached (TN, NO_3-N, and NH_4-N) highly influenced by soil type. Dissolved organic nitrogen was the second largest N leached fraction however it was not significantly affected by soil, treatment or their interaction. Previous studies have observed that leaching was the main pathway of N loss in free draining soils (Bergstrom & Johansson, 1991; Sogbedji et al., 2000; Beaudoin et al., 2005). In this study, both the free draining and moderately draining (Elton and Clonakilty) soils had cumulative leaching losses up to 22.9 kg TN-N ha^{-1}during post-treatment. In comparison, Dennis et al. (2012) recorded between less than one and nine kg N ha^{-1} yr^{-1} from Rathangan and Elton soils respectively, from control and fertiliser treatment based on the same lysimeters in November 2007-November 2008.

Values from this experiment are also on the lower end of the range reported in the literature. Various studies reported NO_3-N leaching after grassland renovation to be between 100 and 300 kg N ha^{-1} yr^{-1}(Davies et al., 2001, Shepherd et al., 2001; Seidel et al., 2007; Velthof et al., 2010). Davies *et al.* (2001) which estimated that 140 kg N ha^{-1} was lost through N_2O and leaching from ploughed and reseeded Scottish grassland over 18 months, while Ball et al. (2007) recorded 25.7 kg NO_3-N ha^{-1} from a free draining ploughed sandy loam soil, as opposed to 12.6 kg NO_3-N ha^{-1} from control over two months. In the current study NO_3-N returned to background within eight months post-renovation.

There is no consensus in the literature on the effect of tillage intensity on N leaching (Oorts et al., 2007; Hansen et al., 2010), with some arguing that greater continuity of large pores under MT would allow greater leaching N loss (Abdalla et al., 2013), and that even with lower NO_3-N concentrations in leachate, the total loss could be higher due to larger volume of water moving through MT soil (Tebrugge & During, 1999). This study adds to the evidence of Hooker et al. (2008) and Premrov et al. (2014) who found no significant difference in leaching from CT and MT soils in Ireland.

4.4 Overall nitrous oxide and leaching losses

Overall, when N_2O and leaching were combined, the total N losses were lowest from poorly and moderately draining soil and highest for the well draining soil, reflecting the dominance of leaching on total N losses (Fig. 4). Additionally, higher WFPS associated with poorly draining soils, and preserved by MT could lead to higher gaseous losses in the form of benign N_2 (McGeough et al., 2012). The proportion of N lost following ploughing and fertilisation from poorly draining soils can reach approximately 30% through leaching and 70% through N_2O, whereas in moderately and free draining soils the leached fraction can be up to 60 to 80%, regardless of the tillage treatment. A shift in the N loss pathway from leaching to N_2O loss was observed on both well and moderately draining soils following adoption of MT, however this trend was not significant. It is commonly perceived that well draining soils are more prone to N leaching (Hansen & Djurhuus, 1997; Beaudoin et al., 2005; Velthof et al., 2010) and poorly draining soils are characterised by large N_2O and N_2 losses (Ball et al., 1999; Davies et al., 2001; Flechard et al., 2007; Harrison-Kirk et al., 2013). Therefore it is deemed important to account for both loss pathways in order to better understand the risk of

N loss through agricultural management.

Timing of renovation also plays an important role in managing risks of leaching and gaseous losses. Velthof et al. (2010) concluded that grassland renovation in autumn increased risk of

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N leaching while renovation in spring mitigated this risk due to quick establishment of plant cover and plant uptake of mineralised N (Necpalova et al., 2013). Grassland renovation in Ireland is commonly performed in autumn therefore leached N which is recognised here as the main loss pathway could be mitigated through adjusting timing of renovation.

Conclusions

Tillage intensity was an important driver of N_2O emissions from the subsequent fertilisations, however only soil significantly influenced total N loss (N_2O + leaching) from ploughing and fertilisations of perennial grassland. Therefore soil type was concluded to be the most important factor controlling the magnitude of overall N losses. This evidence strongly supports the idea of incorporating soil type in agricultural planning and management. The adoption of minimum tillage known to reduce the risk of SOM loss from renovation of perennial grasslands, did not impact either N_2O or N leaching.

Reducing fertilisation rate post planting to account for N mineralised through grassland renovation could reduce the losses. Similarly, the timing of fertilisation could be altered to a period where plant N demand would match N availability. Finally, altered N fertiliser type, such as stabilised urea could further reduce losses. We conclude that N management along with soil type are of vital importance when planning grassland renovation, especially in the case of permanent grasslands which are vulnerable to large losses through mineralisation of highly accumulated SOM.

The authors would like to thank the laboratory and field staff at both Teagasc Johnstown Castle with their assistance on this project. This research was financially supported under the National Development Plan, through the Research Stimulus Fund, administered by the Department of Agriculture, Food and the Marine (07 RSF 527).

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