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Increasing the productivity of an upland pasture with the least environmental impacts

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Highlights

- Production and soil GHG emissions are under researched in upland pastures
- Reseeding, and lime and fertiliser input increased upland grass growth
- Ploughing and rotavating prior to reseeding led to greater soil N_2O emissions
- Pasture metabolisable energy was highest in reseeds in their establishment year
- Lime & fertiliser input to permanent pasture gave lowest yield-scaled N_2O emissions

Abstract

The environmental impacts of increasing pasture productivity in the United Kingdom's (UK) uplands is under-researched. A field trial on a representative upland farm investigated the effect of implementing pasture improvement options on unimproved land between 2017 and 2019. The options were cultivation (ploughing and rotovating) and reseeding in combination with lime and fertiliser inputs. Soil pH, grass growth, pasture quality and nitrous oxide (N_2O) emissions from soil were measured throughout the growing seasons. Carbon dioxide (CO_2) emissions were also measured from cultivation until pasture establishment in 2017. In the year of establishment, reseeding and increased nitrogen (N) fertiliser application led to greater daily grass growth, with the mean over two times greater from the ploughed and reseeded treatment (20.0 kg DM ha^{-1} day^{-1}) as opposed to the control (8.2 kg DM ha^{-1} day^{-1}) during the growing season ($p < 0.05$). Yield effects in subsequent years were dependent upon nutrient input regimes. Despite a significant difference in pasture energy values between the treatments in the year of establishment, there was no effect of reseeding and targeted lime and fertiliser applications on pasture quality in the two subsequent years. Rotovating and ploughing increased soil N_2O emissions, with higher N fertiliser emission factors in 2017 (2.26% ± 0.79 from the rotovated treatment) compared with the IPCC default value of 1.6%. However, low N_2O fluxes in 2018 meant that the emission factors during this growing season were also low (highest value of 0.25% ± 0.04 from the lime and fertiliser input only treatment). Rotovating and ploughing did not significantly impact CO_2 emissions in the establishment period. From a purely production perspective, the results would favour reseeding similarly unproductive upland pastures typical in much of the UK. However, yield-scaled N_2O emission calculations showed that reseeding was not the most effective method in reducing N_2O emissions per unit of grass yield, rather, applying lime and fertiliser resulted in the lowest N_2O emissions per unit of grass produced (0.07 g N_2O kg^{-1} DM of grass). These findings demonstrate the importance of considering both pasture production and N_2O emissions together when improving upland pasture for maximum nitrogen use efficiency and to reduce environmental impacts.

Keywords:

Forage crop, Grassland, Greenhouse gas emissions, Soil cultivation, Sustainable intensification, Upland grazing

1. Introduction

Approximately 42% of the United Kingdom's agricultural land is classified as 'upland' (Reed et al., 2009). Historically, most of this land has been productively poor and the nation's most extensive semi-natural ecosystem (Ratcliffe, 1977). Constraints on the productivity of upland grassland include climatic conditions, acidic soils low nutrient availability (e.g. of nitrogen (N) and phosphorus (P)), restricting plant growth. The introduction of grants to improve upland pasture following the Second World War led to the adoption of practices such as liming, fertiliser applications and reseeding (Frame et al., 1985; Newbould, 1974; 1975). Although very recent data are not available, Fraser (2008) noted that a third of grazed uplands in the UK were now classed as improved pasture (Fraser, 2008), with 26% for Wales (Edwards et al., 2007). These management changes have led to an increase in pasture productivity over time (Cuttle and James, 1995) but the trade-off between pasture productivity gains and environmental impacts remain poorly characterised for upland regions.

Liming of grasslands can improve soil structure (Paradelo et al., 2015) and increase the plant-availability of P and potassium (K) (Karalic et al., 2013), improving grass yield (Mazzetto et al., 2015) and persistence of perennial species (Hayes et al., 2016). However, liming can contribute to greenhouse gas (GHG) emissions from agricultural soils (IPCC, 2006). Nitrogen fertiliser is applied to increase plant-available N, enhancing yield and improving quality through increased crude protein content (Keady et al., 2000). Over-application of N fertiliser, however, leads to increased secondary environmental burdens such as nutrient leaching, causing eutrophication in watercourses (Leip et al., 2015). Lastly, nitrogen fertiliser inputs are a major driver of the emissions of the powerful GHG, N_2O, from pasture (Poulton et al., 2018; Cardenas et al., 2010; Lampe et al., 2006).

It is often suggested that reseeding is a necessary requirement in order to change pasture composition and maintain, or improve, grassland productivity (Bertora et al., 2007; Rushton et al., 1989). However, reseeding is not always practical in the uplands due to physical features (e.g. steep terrain and remoteness) restricting access (Fraser et al., 2014). The costs of establishment can then outweigh the increase in productivity (Mansfield, 2011). Previous research has also confirmed that ploughing grassland for renovation is responsible for a substantial amount of N_2O emissions (Vellinga et al., 2004).

As stated above, although measures intended to improve pasture productivity are known to have potentially negative environmental impacts, there is some paucity of research quantifying these impacts in the uplands and the extent to which these may be compensated by productivity gains. The emission factor (EF) for N_2O emissions has recently been revised from a default value of 1% taking into account climate and fertiliser type, leading to an amended value of 1.6% for synthetic N fertiliser applied to managed agricultural soils in wet climates (IPCC, 2019). However, few studies have attempted to calculate the N_2O EF following N fertiliser inputs to previously unfertilised upland soils, which differ in environmental factors and land management compared to intensive lowland agriculture. Similarly, studies on the impacts of liming on soil N_2O emissions have largely focused on lowland and arable soils (Shaaban et al., 2019; Baggs et al., 2010). Lastly, direct comparisons of N_2O emitted from upland agricultural soils following ploughing and rotavating (a pre-requisite of reseeding) are very limited.

While applying lime and fertiliser may increase upland pasture production in permanent pastures or reseeds, there is a need to investigate the environmental impacts of such measures, particularly any changes to GHG emissions. In this study, we hypothesised that pasture improvements commonly applied in the UK uplands, including reseeding and/or lime plus fertiliser applications, besides the anticipated positive changes on herbage productivity and quality, would have also important environmental consequences, such as negative changes in GHG emissions and soil characteristics. In light of the important knowledge gaps, we designed a trial on an upland site, over multiple years, in order to test the above hypothesis and estimate the environmental trade-offs of the pasture improvement practices. The findings could help identify opportunities to increase production efficiencies of upland pastures, while reducing the associated environmental burden.

2. Materials and methods

2.1 Study site - Establishment and set-up

The experiment was conducted at Henfaes Research Centre, Abergwyngregyn, north Wales, with the study site located at approximately 236 m a.s.l. (53.23°N, 4.01°W). The mean long-term annual rainfall at the site is 1282 mm, and time-series data for air and soil temperature are available from the UK Centre for Ecology and Hydrology (2020). Rainfall totals for the growing seasons (May - September) for the experimental years were as follows: 654.4 mm, 422.9 mm, 548.8 mm for 2017, 2018 and 2019, respectively (Boorman, 2019; personal communication). The site was previously grazed by sheep, but stock were excluded for experimental purposes and the study treated as a simulated grazing experiment, with regular sward cutting. There have been no interventions (nutrient or lime additions) to the site since the early-1980s.

The site measured approximately 943 m^2 (23 m × 41 m) and was set out in a randomised complete block design. In the first year of the study (2017), the site consisted of fifteen 9 m × 4 m plots with a 1 m buffer between each plot. There were five treatments: (a) Control (C); b) Rotovate, spring forage rape followed by autumn grass reseed, lime and fertiliser input (R-FR-G-LF); c) Plough, spring grass reseed, lime and fertiliser input (P-G-LF); d) Rotovate, spring grass reseed, lime and fertiliser input (R-G-LF); e) Lime and fertiliser input only (LF)), with three replicates of each (Fig. 1). Subplots in a split-plot design were set-up in the second year (2018), leading to a total of thirty 4 m × 4 m plots separated by a 1 m buffer for the duration of 2018 and 2019. The treatments are described in Table 1.

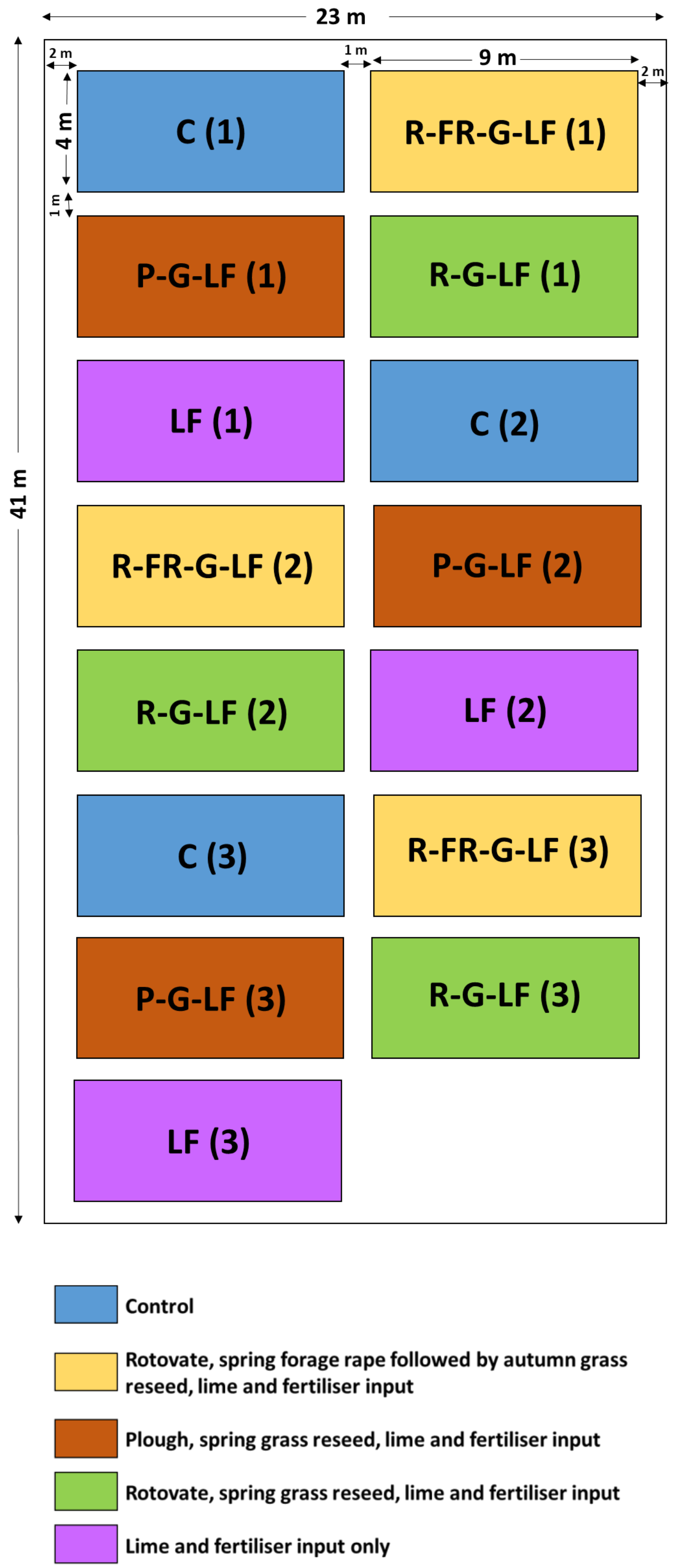

Fig. 1. Experimental plot layout in 2017. Each plot was divided to subplots in a split-plot design in 2018.

Table 1. Nutrient application and management regimes of the different treatments (C – Control; R-FR-G-LF – Rotovate, spring forage rape followed by autumn grass reseed, lime and fertiliser input; P-G-LF – Plough, spring grass reseed, lime and fertiliser input; R-G-LF – Rotovate, spring grass reseed, lime and fertiliser input; LF – Lime and fertiliser input only). The range in lime and fertiliser application rates is the replicates' application range for that treatment, based on soil analyses. Fertiliser application rates were determined following soil analyses, in accordance with recommendations in the Nutrient Management Guide (RB209), 8th edition (AHDB, 2017b) for 2017 and split-plots A, and typical application rates in the British Survey of Fertiliser Practice (2017) for split-plots B.

		2017					2018				2019			
Treatment code	Treatment description	Lime application (kg ha^{-1})		Fertiliser application (kg ha^{-1})			Lime application (kg ha^{-1})	Fertiliser application (kg ha^{-1})			Lime application (kg ha^{-1})	Fertiliser application (kg ha^{-1})		
		Spring application	Autumn application	Nitrogen	Phosphorus	Potassium		Nitrogen	Phosphorus	Potassium		Nitrogen	Phosphorus	Potassium
C	Control	-	-	-	-	-	-	-	-	-	-	-	-	-
R FR G	Rotovate, spring forage rape followed by autumn grass reseed, lime and fertiliser input	440 - 995	770 - 940	90	0 – 55	80	375 - 675	A – 130 B - 50	20 - 110	340	495 - 770	A – 130 B - 50	80 - 140	160 - 250
P G	Plough, spring grass reseed, lime and fertiliser input	330 - 1050	330 - 770	60	50 - 80	80	150 - 375	A – 130 B - 50	90 - 120	360-410	440 - 895	A – 130 B - 50	80 - 110	160 - 250
R G	Rotovate, spring grass reseed, lime and fertiliser input	440 - 1050	385 - 770	60	0 - 80	80	75 - 675	A – 130 B - 50	120 - 150	360 - 410	495 - 715	A – 130 B - 50	80 - 140	160 - 250
I	Lime and fertiliser input only	495-885	330-605	60	20	30	0-375	A – 130 B – 50	110 - 140	290 - 340	385 - 715	A – 130 B - 50	95 - 125	170 - 210

2.2 Treatment specifications

2.2.1 2017

Soil samples were collected from each plot prior to any operations. A minimum of five subsamples were taken from each plot in a 'W' pattern using a soil corer (0 – 10 cm). The subsamples were combined to produce a composite sample from each plot, which was analysed for pH, P, K, magnesium and sulphur (analysed by NRM Laboratories, Bracknell, Berkshire). Lime and fertiliser applications for each independent plot were determined based on soil analyses in accordance with recommendations in the Nutrient Management Guide (RB209), 8th edition (AHDB, 2017b). Fertiliser was applied as Ammonium Nitrate (AN), Triple Super Phosphate (TSP) and Muriate of Potash (MOP) to all treatments at the same time on 16 May, 2017. Granulated Lime, 36% calcium (Calcifert, Runcorn, Cheshire) was applied on 16 May, 2017 for rapid effect, with the target pH for grasslands set at 6.0. Further soil sampling was conducted on 30 August, 2017, and a second application of lime was applied on 25 October, where needed.

Prior to any field operations, the three treatments that required reseeding were sprayed with Glyphosate (Rosate 36) at a rate of 4 L ha^{-1}. The grass seed mixture sown on 16 May, 2017 was trade name 'Lambhill' (Limagrain UK Ltd., Rothwell, Lincolnshire), a long-term mixture for marginal land consisting of 66% perennial ryegrass (*Lolium perenne L.*), 13% timothy (*Phleum pratense*), 7.5% creeping red fescue (*Festuca rubra*), 5.5% white clover (*Trifolium repens*), 5% meadow fescue (*Festuca pratensis*) and 3% alsike clover (*Trifolium hybridum*), sown at a rate of 45 kg ha^{-1}. Where establishment was not achieved due to the dry weather conditions, plots were re-sown a month later. For the forage crop treatment, a rape/kale hybrid ('Interval', Limagrain) was sown at 8 kg ha^{-1}. This was sown as a "break crop" (a short-term crop grown between reseeding grass into grass; AHDB, 2017a) and was harvested on 23 August, 2017. A subsample of each pasture was extracted for 'wet' Near Infrared analysis of ruminant metabolisable energy (ME) and crude protein content (analysed by Sciantec Analytical Services Ltd., Stockbridge Technology Centre, Cawood). The forage rape treatment plots were reseeded with 'Lambhill' grass mixture on 26 September, 2017.

2.2.2 2018 and 2019

As in 2017, soil sampling was conducted prior to lime and fertiliser application. The recommended rate of N application for grazed swards with an indicative dry matter (DM) yield of 7-9 t ha^{-1} in the Nutrient Management Guide (RB209) (AHDB, 2017b) is 130 kg N ha^{-1}, whereas typical application rates and overall nitrogen use for grassland was 54 kg N ha^{-1} in 2017, according to the British Survey of Fertiliser Practice (DEFRA, 2018). To investigate the impacts of such differences on both pasture productivity and N_2O emissions, we implemented a split-plot design in 2018 of the five treatments set up in 2017. For split-plots A, nitrogen inputs in the form of AN were applied according to the recommended rates of three split doses of 50 kg N ha^{-1}, 40 kg N ha^{-1}, 40 kg N ha^{-1} (ADHB, 2017b), and for split-plots B, as a single application of 50 kg N ha^{-1}.

2.3 Measurements

2.3.1 Grass growth and quality

During the growing season, sward height was measured on a weekly basis using a calibrated rising Jenquip EC09 electronic plate meter (Handley Enterprises Ltd., Sixpenny Handley, Salisbury) within the plots. Grass samples were obtained for biomass yield by cutting a 1 m × 1 m quadrat from each plot. The timing of collecting grass samples was dependent on grass growth, with samples cut to mimic cattle grazing, thus when the sward was approximately 8–11 cm. This resulted in three separate sampling occasions in 2017, two sampling occasions in 2018, and three sampling occasions in 2019. The samples were then analysed as before, to calculate crude protein content and ME value.

2.3.2 Monitoring nitrous oxide and carbon dioxide emissions

A closed static chamber (40 cm × 40 cm × 25 cm) was assigned to each plot, with air samples for GHG analysis (20 ml) collected prior to any treatment application (Cardenas et al., 2016). Three time points were taken per chamber (t0 = 0 min, immediately after closing lid of the chamber; t1 = 30 min; t2 = 60 min). The samples were stored in pre-evacuated 20 ml glass vials. The initial gas samples provided a baseline flux before treatments were introduced. Sampling frequency was dependent on field operations' timings. The samples were analysed for N_2O (μg N_2O-N m^{-2} h^{-1}) and CO_2 (g CO_2 m^{-2} h^{-1}) emissions using a Varian 450 Gas Chromatograph, with the N_2O and CO_2 fluxes calculated by assuming a linear interpolation from t0 (ambient) to t60 (Smith and Dobbie, 2001). It has been demonstrated that the closure period for chambers of these dimensions results in linear increases in headspace N_2O concentrations over a 60 minute period from typical N sources applied to soil (Chadwick et al., 2014). Furthermore, this approach has been used for quantifying N_2O flux measurements following N applications to grassland (Cardenas et al., 2019). Guidance on the use of the closed static chamber approach and assuming a linear increase in concentration for CO_2 is, however limited. We acknowledge that this increases the complexity of obtaining accurate CO_2 flux measurements, whereby flux underestimation due to potential increase of CO_2 headspace concentrations may occur. Nevertheless, comparisons of the closed static chamber and the closed dynamic chamber have determined that both approaches can provide comparable CO_2 flux measurements when initially sampling (Heinemeyer and McNamara, 2011). An automatic weather station near the experimental site provided half-hourly temperature measurements, which were used to calculate the gas fluxes (data owned by NERC – Centre for Ecology and Hydrology).

2.4 Calculations and statistical analyses

Statistical analyses and graphical representations were conducted using packages in R (R Core Team, 2019). A randomised blocked one-way ANOVA was used to determine the difference between treatments and the block effect for grass growth. This was followed by a Tukey post-hoc test. Significance was concluded at the $p < 0.05$ level. The N_2O and CO_2 fluxes were calculated by the method described in Chadwick et al. (2018). Cumulative N_2O and CO_2 emissions were calculated by trapezoidal integration between sampling points. The N_2O emissions were accumulated over 184 days in 2017 (31 sampling occasions), 302 days for the original five treatments in 2018 (32 sampling occasions), and 199 days for split-plots (B) in 2018 (27 sampling occasions). A seasonal cumulative CO_2 emission was measured over 100 days post cultivation in 2017 to monitor CO_2 fluxes from cultivation to pasture establishment (23 sampling occasions), with a seasonal cumulative N_2O emission determined for the same length of time to compare N_2O and CO_2 data. Differences in N_2O flux were also compared via a one-way ANOVA. N_2O EFs were calculated by expressing the N_2O emitted from the treatments as a percentage of the N fertiliser applied (equation in Marsden et al., 2016). The baseline control mean was calculated as the mean effect across the three blocks in each blocked one-way ANOVA performed. Control 1 was removed from the N_2O calculations in 2018 due to an anomaly of exceedingly high peaks for this replicate. The seasonal Global Warming Potential (GWP) was determined via the conversion of the seasonal cumulative CO_2 from CO_2-C to CO_2, and seasonal cumulative N_2O from N_2O-N to N_2O. The CO_2 equivalent of the seasonal cumulative N_2O was calculated by multiplying with its GWP (298) and adding the resulting value to the seasonal cumulative CO_2 for each treatment. For the yield-scaled N_2O emissions, the cumulative N_2O emissions per treatment for the 2017 N_2O sampling period of 184 days was used to calculate a daily N_2O emission value for each treatment. The yield-scaled emissions were not calculated for 2018 due to very low N_2O data in 2018, a consequence of the major drought experienced during the sampling period. For the grass yield, total grass production values for the monitored period (224 days for grass measurements) were used to calculate a daily grass production value for each treatment. The data were converted to a daily production figure for both N_2O emissions and pasture production to give a comparable estimate due to the variation in days of measurements. Daily N_2O emission values were divided by daily grass production values to give the daily yield-scaled emissions for each treatment in order to determine the most efficient treatment in maximising pasture production, at least GHG cost. The daily yield-scaled emissions were expressed as g N_2O kg^{-1} DM of grass produced day^{-1}.

3. Results

3.1 Grass growth and soil pH

3.1.1 2017

Grass growth was significantly greater in the reseeded plots than the control plots over the 2017 growing season ($p < 0.05$) (Fig. 2). The mean daily grass growth was 20.0 kg DM ha^{-1} day^{-1} for the ploughed and reseeded treatment and 18.7 kg DM ha^{-1} day^{-1} for the rotovated and reseeded treatment. In addition to this, the mean daily grass growth was higher following lime and fertiliser input (12.1 kg DM ha^{-1} day^{-1}) compared to the control (8.2 kg DM ha^{-1} day^{-1}). This was particularly evident at the peak of the growing season (July – September). Despite this, there was no statistically significant difference in seasonal grass growth between the lime and fertiliser input only treatment and all other treatments (Table 2).

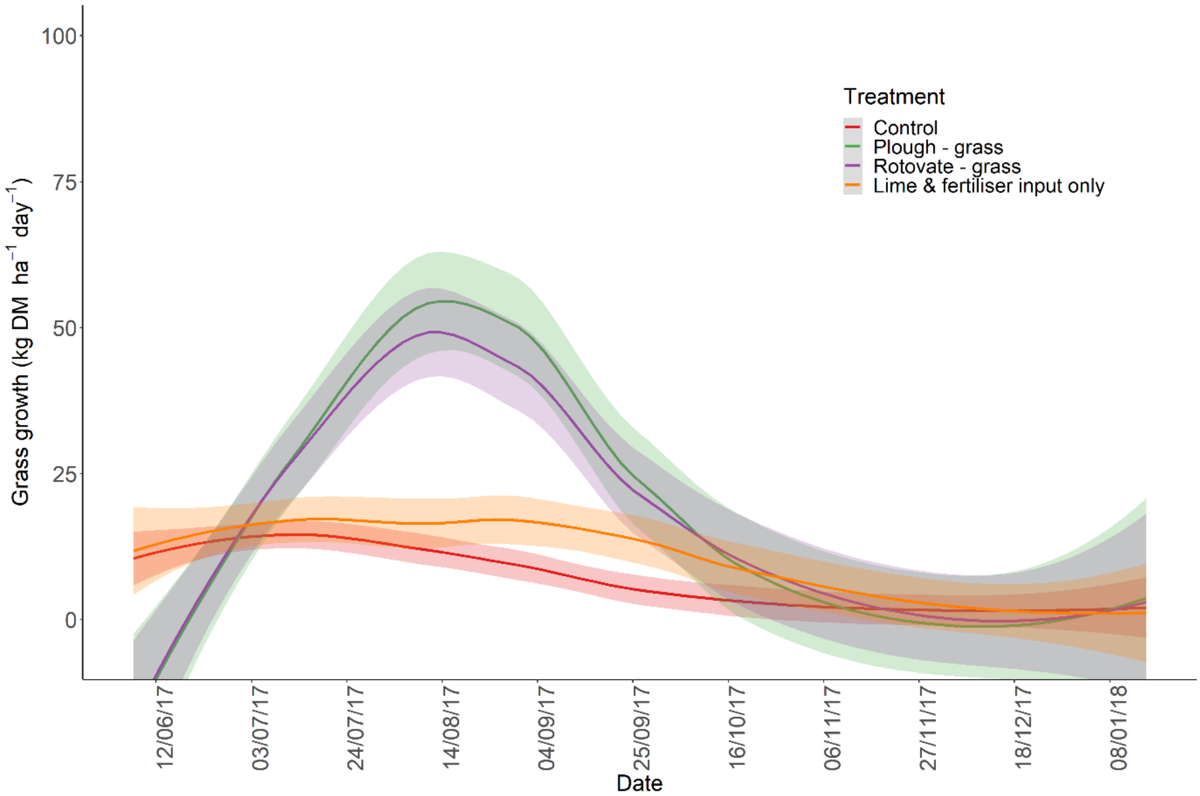

Fig. 2. Mean daily grass growth of the treatments over 2017 sampling period. Dates are expressed in dd/mm/yy. Coloured lines represent the treatment means (n = 3) and the shaded areas represent the upper and lower bounds of the standard error of the mean (SEM) and appear to exceed the minimum value on the *y*-axis due to the nature of the smoothing curve.

Table 2. Daily average grass growth in 2017 (- indicates no results due to autumn grass reseed, so no production measurements for that treatment, n = 3 otherwise). Treatments with different letters are significantly different at $p < 0.05$ ± = SED.

Treatment	Grass growth (kg DM ha^{-1} day^{-1})
Control	8.22^{a} ± 2.73
Forage crop – grass	-
Plough – grass	20.00^{b} ± 3.15
Rotovate – grass	18.72^{b} ± 3.15
Lime and fertiliser input only	12.09^{ab} ± 3.15

3.1.2 2018 and 2019 with split-plot nitrogen application

Variation in soil pH following lime application is provided in the Supplementary material (Fig. S1). The mean soil pH was higher at the beginning of 2018 for the treatments that received lime, indicating the positive effect of applying lime. Despite this, the average pH displayed a declining trend in most treatments, apart from the forage crop - grass treatment which remained fairly consistent. The mean soil pH of the plots was 5.9 ± 0.09 on the last sampling date. There was a significant difference in soil pH between the control and improved treatments during this period, once again indicating the effect of lime application in raising soil pH. The blocked one-way ANOVA indicated there was no significant block effect between the three blocks ($p > 0.05$).

For 2018, there was no significant difference in grass growth per day between the treatments that received 50 kg N ha^{-1} (Fig. 3a); likewise when treatments received 130 kg N ha^{-1} (Fig. 3c). However, daily grass growth more than doubled, and was significantly higher from the reseeded treatments following a total of 130 kg N ha^{-1} applied when compared with a single dose of 50 kg N ha^{-1} application. There was a significant difference between the three reseeded (forage crop - grass at 23.7 kg DM ha^{-1} day^{-1}, plough - grass at 18.5 kg DM ha^{-1} day^{-1} and rotovate – grass at 21.7 kg DM ha^{-1} day^{-1}) treatments that received 130 kg N ha^{-1} and the control treatment (3.7 kg DM ha^{-1} day^{-1}) (Fig. 3c). In addition to this, mean grass growth per day was significantly higher from the forage crop – grass 130 kg N ha^{-1} treatment (23.7 kg DM ha^{-1} day^{-1}) than the forage crop – grass 50 kg N ha^{-1} (8.6 kg DM ha^{-1} day^{-1}), plough – grass 50 kg N ha^{-1} (4.8 kg DM ha^{-1} day^{-1}), rotovate – grass 50 kg N ha^{-1} (7.3 kg DM ha^{-1} day^{-1}) and lime and fertiliser input only (5.6 kg DM ha^{-1} day^{-1}) 50 kg N ha^{-1} treatments ($p < 0.05$). Daily grass growth was also significantly greater in the rotovated treatments that received the highest N application than the plough – grass and lime and fertiliser input that was applied 50 kg N ha^{-1} ($p < 0.001$).

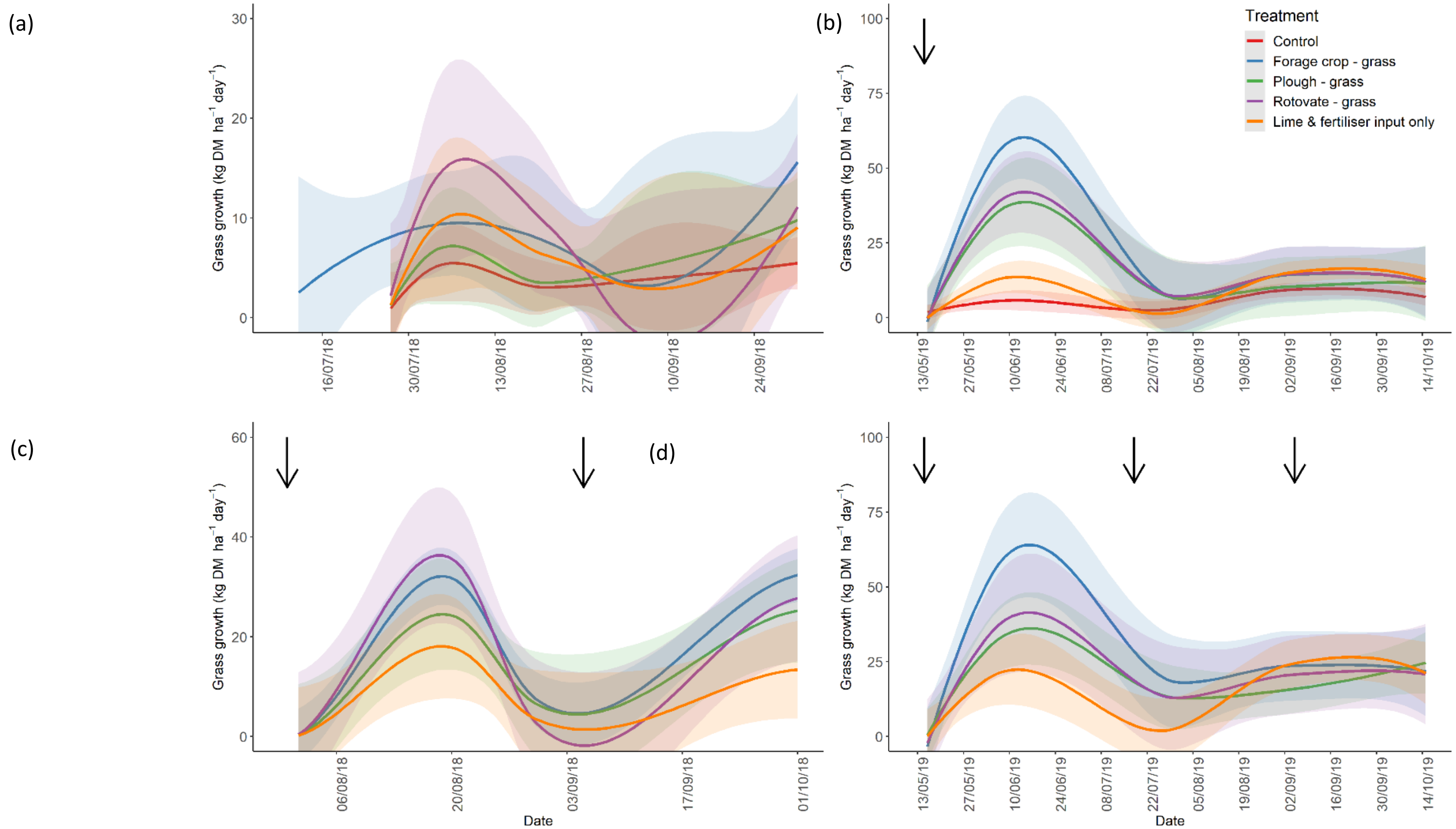

Fig. 3. Mean daily grass growth of the treatments that received a total of (a) 50 kg N ha^{-1} in 2018, (b) 50 kg N ha^{-1} in 2019, (c) 130 kg N ha^{-1} in 2018 and (d) 130 kg N ha^{-1} in 2019 sampling period. Dates are in dd/mm/yy format. Coloured lines represent the treatment means (n = 3) and the shaded areas represent the upper and lower bounds of the SEM. Arrows denote timing of N fertiliser applications. The first N fertiliser application was made prior to

grass growth sampling in 2018. Forage crop – grass treatment curve in (a) commences at an earlier date due to the timing of the sward cuts. Rotovate – grass curve in (a) along with the shaded areas in all plots appear to exceed the minimum value on the *y*-axis due to the nature of the smoothing curve.

For 2019, daily grass growth was also greater from the treatments that received 130 kg N ha^{-1} (Fig. 3d) compared to 50 kg N ha^{-1} (Fig. 3b). However, the extent of the difference was not as prominent as in 2018, with no significant effect of N application rate. Despite this, mean daily grass growth was significantly greater in both the forage crop – grass treatments (50 kg N ha^{-1} at 21.4 kg DM ha^{-1} day^{-1} and 130 kg N ha^{-1} at 27.1 kg DM ha^{-1} day^{-1}) than the control (6.3 kg DM ha^{-1} day^{-1}) in 2019.

3.2 Grass quality

There was no significant block effect in grass quality ($p > 0.05$) (Fig. 4). However, the ME value was significantly higher from the reseed treatments in comparison with the permanent pasture treatments ($p < 0.05$). There was no significant effect of treatments on crude protein content.

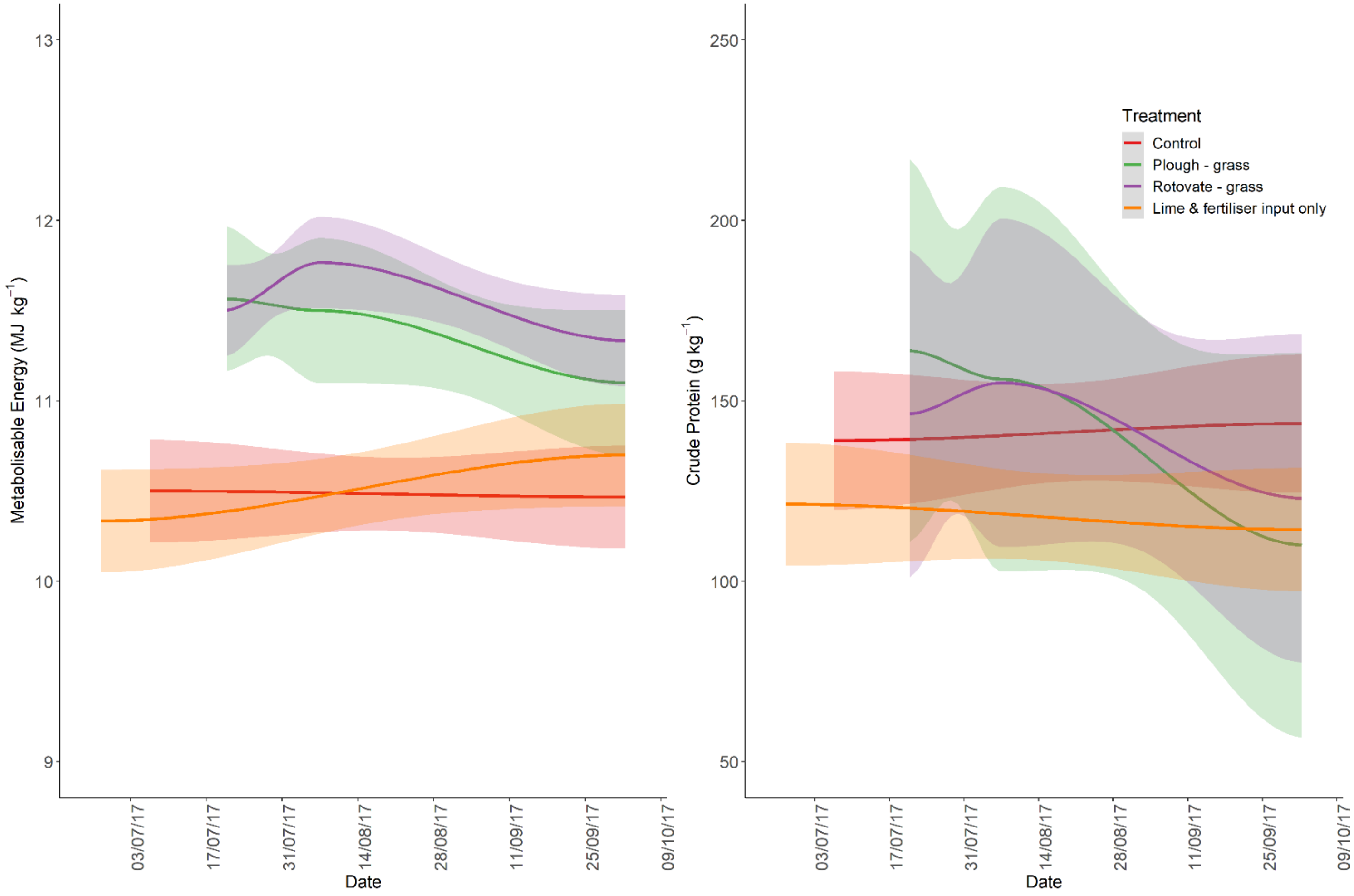

Fig. 4. Metabolisable energy and crude protein values of the treatments during the 2017 sampling season. Coloured lines represent the treatment means (n = 3) and the shaded areas represent the upper and lower bounds of the SEM. Dates are in dd/mm/yy format. The control and lime and fertiliser input

only treatments commence at an earlier date due to the timing of the sward cuts. Shaded areas in the crude protein plot appear to exceed the minimum value on the *y*-axis due to the nature of the smoothing curve.

Both ME and crude protein values were not significantly different between all treatments in both 2018 and 2019 (Fig. 5). The ME value, although insignificantly different, was the highest in the forage rape – autumn grass reseed treatment in both years (11.8 MJ kg^{-1}, equal highest value recorded with the plough – grass treatment in 2018 and 11.9 MJ kg^{-1} in 2019). Of the grass only treatments, the ME value was higher in the reseeded treatments.

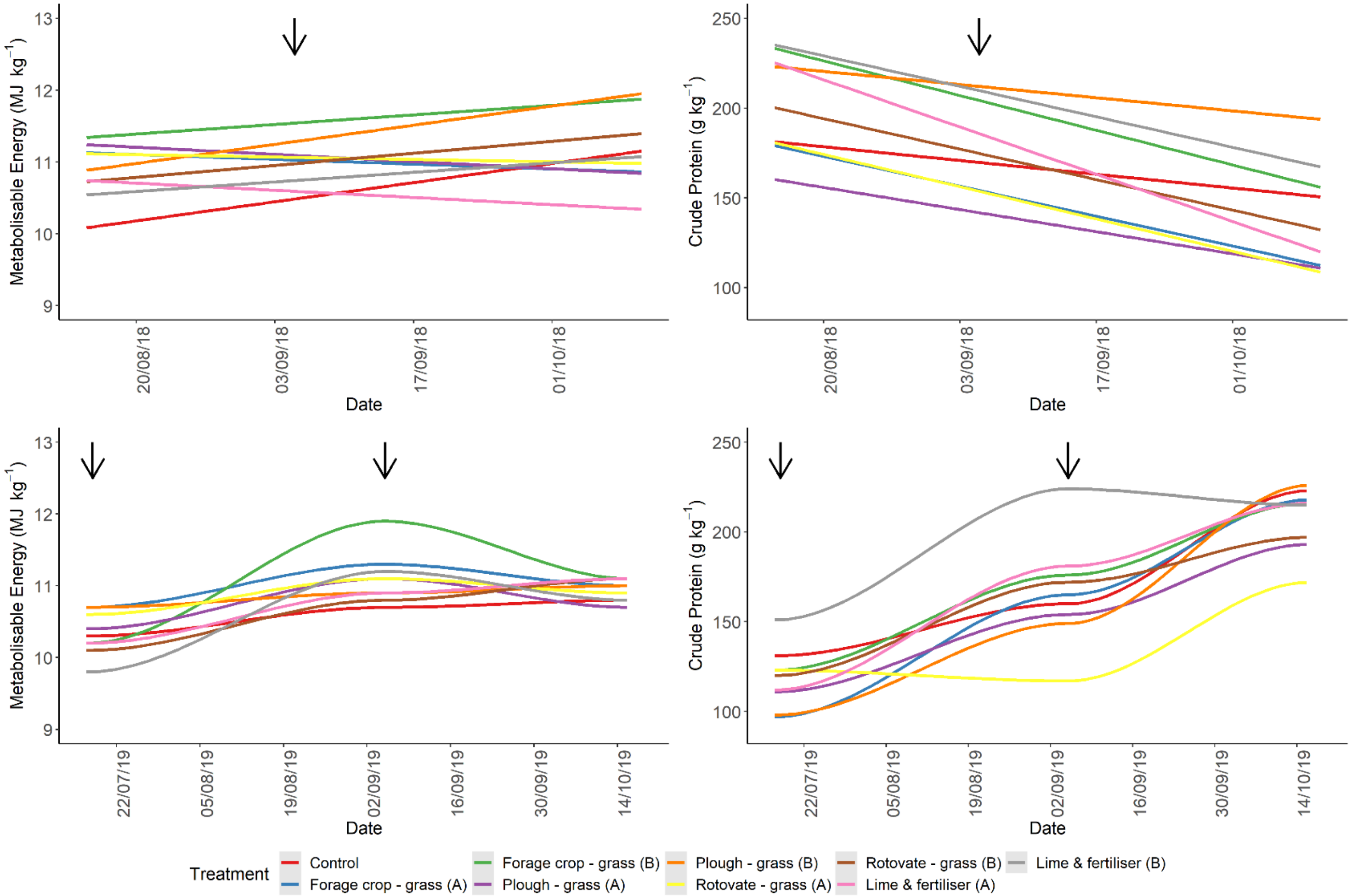

Fig. 5. Metabolisable energy and crude protein values of the treatments during the 2018 and 2019 sampling season. Coloured lines represent bulked samples of each treatment. (A) and (B) denote N fertiliser application rates (see Table 1) and the arrows denote application timings during the sampling

seasons. Dates are in dd/mm/yy format. The first two N fertiliser application were made prior to grass quality analysis in 2018. The first N fertiliser application was also made prior to grass quality analysis in 2019.

The crude protein content was numerically (but not significantly) greater from the treatments that received 130 kg N ha^{-1} in both years, with the greatest values being 228 g kg^{-1} deriving from the lime and fertiliser input only treatment in 2018, and 226 g kg^{-1} from the plough - grass treatment in 2019. In 2018, the crude protein content of all treatments decreased as the monitoring period progressed. In contrast, the crude protein content increased during the 2019 growing season for all treatments.

3.3 Nitrous oxide and carbon dioxide emissions

3.3.1 Measured fluxes

The rotovated - grass treatment had the largest N_2O fluxes between 12 May, 2017 and 28 June, 2017, with average peaks of 174.30 μg N_2O-N m^{-2} h^{-1} and 166.00 μg N_2O-N m^{-2} h^{-1} observed for this treatment on 7 June, 2017 and 14 June, 2017, respectively (Fig. 6). The treatments implemented had a significant impact on the N_2O emissions (Table 3). N_2O emissions from the treatments in 2018 are displayed in Supplementary material (Fig. S3). Every treatment produced low N_2O fluxes throughout 2018. There was no significant difference between any of the treatments, indicating that greater and more frequent N fertiliser applications had no effect on N_2O emissions from this soil during the sampling period.

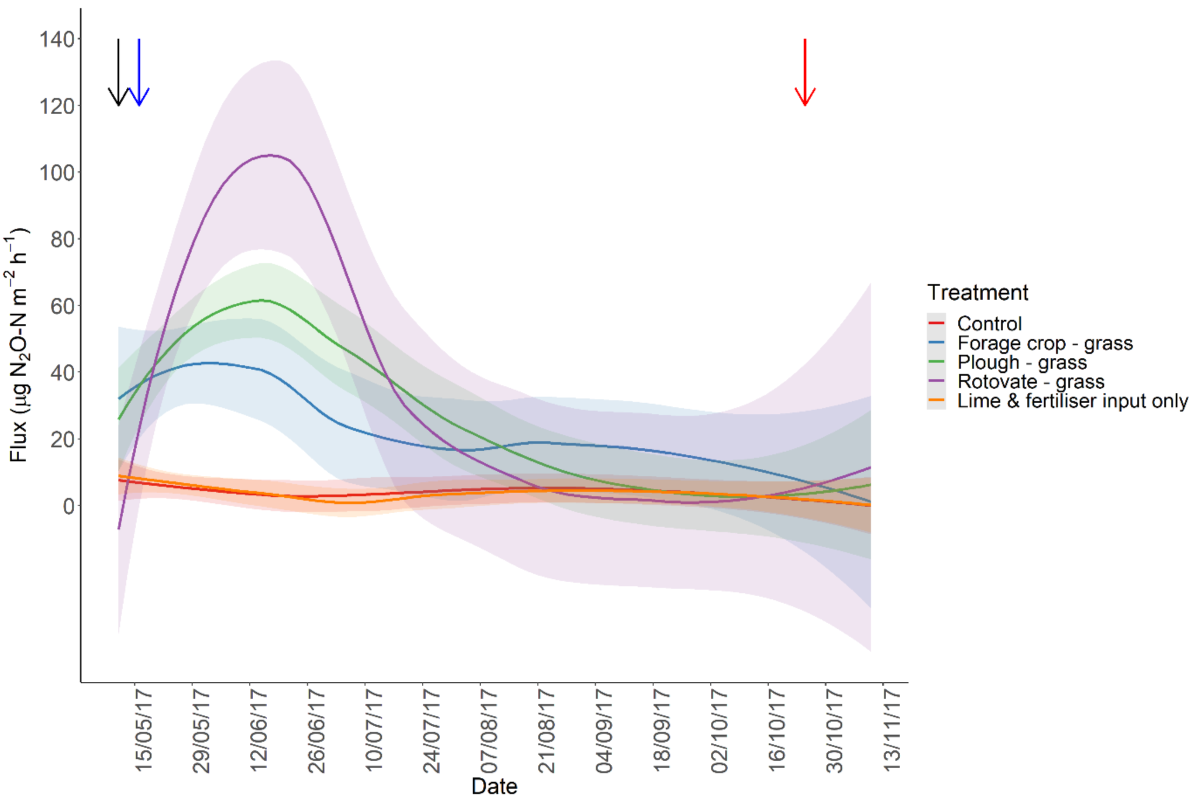

Fig. 6. Nitrous oxide (μg N_2O-N m^{-2} h^{-1}) emissions from the treatments in 2017. Coloured lines represent the treatment means (n = 3) and the shaded areas represent the upper and lower bounds of the SEM. Dates are in dd/mm/yy format. Amendments were made at the points of the arrows. The black arrow denotes the ploughing and rotovating, the blue arrow denotes the sowing date as well as lime and fertiliser application and the red arrow denotes a second lime application in the autumn. Shaded areas appear to exceed the minimum value on the *y*-axis due to the nature of the smoothing curve.

Table 3. Average hourly nitrous oxide emissions from the experimental treatments for the 2017 grow ing season (n = 3, treatments with different letters are significantly different at $p < 0.05$ ± = SED).

	Flux (μg N_2O-N m^{-2} h^{-1})
Control	$4.65^{a} \pm 5.10$
Forage crop - grass	$27.52^{b} \pm 6.12$
Plough - grass	$31.70^{b} \pm 6.02$
Rotovate - grass	$37.35^{b} \pm 5.99$
Lime and fertiliser input only	$4.24^{a} \pm 6.14$

Cultivation and ploughing in particular did not lead to greater C loss via CO_2 fluxes as expected (Fig. S2). The CO_2 emissions produced for the 100 days from cultivation to pasture establishment were negligible.

3.3.2 Cumulative greenhouse gas emissions and nitrous oxide emission factors

There was no significant relationship between the seasonal cumulative CO_2 emissions and ploughing (Table 4). In 2017, the N_2O EFs from the rotovate – grass treatment was moderately large (2.26%) compared to the present default EF of 1.6% of N applied as fertiliser for direct emissions from agricultural soils (IPCC, 2019). Statistical analysis revealed that treatments had no effect on cumulative N_2O emissions in both 2017 and 2018. Furthermore, ploughing and rotovating early in the summer had no significant effect on the overall EFs for the 2017 sampling period. Both the cumulative emissions and EFs from 2018 were low compared to 2017 results and the IPCC default value, with no significant effect of varying rates of N fertiliser applications. In relation to the stage of establishment and grass growth, the cumulative N_2O emissions and EFs values were greater in 2017 than 2018; a similar finding to the N_2O fluxes (Fig. 6).

Table 4. Cumulative nitrous oxide emissions and emission factors for the various treatments in 2017 and 2018 (n = 3, ± SEM). (B) treatments refer to the split-plot subplots in 2018 (see Table 3.1). Seasonal cumulative CO_2 and N_2O in 2017, as well as global warming potential are calculated for the first 100 days post cultivation. Total cumulative N_2O in 2017 is based on a sampling period of 184 days post cultivation. Cumulative N_2O in 2018 is based on a sampling period of 302 days for original 5 treatments and 199 days for the split-plot (B) treatments.

Treatment	2017					2018	
	Seasonal cumulative CO_2 (kg CO_2-C ha^{-1})	Seasonal cumulative N_2O (kg N_2O-N ha^{-1})	Seasonal global warming potential (kg CO_2e ha^{-1})	Cumulative N_2O (kg N_2O-N ha^{-1})	Emission factor (% of N applied)	Cumulative N_2O (kg N_2O-N ha^{-1})	Emission factor (% of N applied)
Control	705.66 ± 218.80	0.08 ± 0.04	2623.63 ± 820.65	0.14 ± 0.05	-	0.02 ± 0.05	-
Forage crop – grass	333.86 ± 37.02	0.69 ± 0.20	1547.89 ± 221.40	0.91 ± 0.26	0.86 ± 0.34	0.02 ± 0.11	-0.03 ± 0.17
Forage crop – grass (B)	-	-	-	-	-	0.12 ± 0.02	0.07 ± 0.03
Plough – grass	872.53 ± 215.46	0.91 ± 0.16	3626.29 ± 732.60	1.07 ± 0.25	1.55 ± 0.43	-0.01 ± 0.03	-0.08 ± 0.05
Plough – grass (B)	-	-	-	-	-	0.15 ± 0.05	0.09 ± 0.04
Rotovate – grass	821.40 ± 31.04	1.33 ± 0.72	3634.84 ± 300.27	1.50 ± 0.77	2.26 ± 1.36	0.02 ± 0.02	-0.03 ± 0.04
Rotovate – grass (B)	-	-	-	-	-	0.10 ± 0.06	0.05 ± 0.00
Lime and fertiliser input only	1028.63 ± 206.41	0.07 ± 0.03	3802.51 ± 768.49	0.13 ± 0.03	-0.01 ± 0.05	0.16 ± 0.03	0.25 ± 0.04
Lime and fertiliser input only (B)	-	-	-	-	-	0.05 ± 0.02	0.01 ± 0.02

3.4 Daily yield-scaled nitrous oxide emissions

The N_2O emissions along with pasture production data for 2017 were used to calculate the daily yield-scaled emissions. Data for 2018 were omitted due to the abnormal environmental conditions (a major drought) during the sampling period leading to negligible fluxes. The highest daily yield-scaled emissions resulted from the rotovated treatment and the lowest yield-scaled emissions were produced by the lime and fertiliser input only treatment (Table 5).

Table 5. Daily yield-scaled N_2O emissions for the treatments in 2017 (- indicates no results due to autumn grass reseed, so no production measurements). (- indicates no results due to autumn grass reseed, so no production measurements).

Treatment	Daily yield-scaled emissions (g N_2O kg^{-1} DM of grass produced day^{-1})
Control	0.11
Forage crop - grass	-
Plough - grass	0.33
Rotovate - grass	0.48
Lime and fertiliser input only	0.07

4. Discussion

4.1 Comparative grass production and quality

Daily grass growth was significantly greater following reseeding when compared to the permanent pasture treatments in 2017. At the peak of the growing season during this year, daily grass growth doubled for the reseeded treatments compared to permanent pasture treatments. It is well-known that reseeding is an effective method of increasing pasture response to fertiliser, as noted by AHDB (2017a). Carswell et al. (2019) reported that in the first year following reseeding in lowland sites, pasture productivity was greater in the new sward as opposed to permanent pasture. However, they reported no significant yield improvement from the reseeded swards relative to permanent pasture in subsequent years. Comparisons between studies should be done with caution due to differing climate, soil and environmental factors. Our study was conducted on one site, however it is reflective of many other upland regions due to its typical upland characteristics and management regime.

The grass growth curves of the reseeded treatments in 2018 and 2019 (Fig. 3) are comparable with the trends of a UK multi-site industry-led project, “Forage for Knowledge” (AHDB, 2020). Daily grass growth at the peak of the growing season was higher for the Forage for Knowledge project compared to our study. However, their project collected data from various organic and conventional dairy farms across Great Britain, where expected yields would be notably greater than for an upland site such as that used in our study. In 2019, daily grass growth was greater from the forage crop – grass treatments than the other treatments. The value of break crops such as forage rape in reducing the burden of disease and pests on new reseeds is acknowledged (AHDB, 2017a); though requires further study in an upland context.

We hypothesised that pasture improvements such as in the form of reseeding, lime or fertiliser applications would lead to increased grass production. The findings presented here support this, with the lowest daily grass growth from 2017 - 2019 recorded in the control treatment (Fig. 2 and 3).

Applying N in accordance with the RB209 guidelines led to significantly higher daily grass production as opposed to the typical application rates reported in the British Survey of Fertiliser Practice ($p < 0.05$) (Fig. 3). Although daily grass growth in 2019 was also greatest from the treatments that received N fertiliser in accordance with RB209 recommendations, the variation in daily grass growth between the treatments were far less in 2019 in comparison with 2018. To our knowledge, this is the first study to compare differences in grass growth between N applied in industry advice (AHDB, 2017b) with common practice, as measured by the British Survey of Fertiliser Practice (DEFRA, 2018). Although we found that RB209 recommendations led to increased grass growth, there would be an additional economic cost to this approach. It is also important to note that the pasture yield response to additional N inputs in our study may also not be seen where grass growth is affected by factors such as climate, differences in sward species, and also insufficient supply of nutrients other than N. Further work is necessary to determine the economic cost-benefits of variable N application rates on a range of pasture productivity gradients.

In our study, the pasture ME value was significantly higher from the reseeded treatment in comparison with the permanent pasture treatments during the establishment year. However, this difference was not evident between the treatments in the two subsequent study years. The crude protein content was highest in the ploughed treatment that received 130 kg N ha^{-1}, at 226 g kg^{-1} for one of the replicates at its peak in 2019 (Fig. 5). The ME value was highest in the forage crop – grass treatment in the same year, peaking at 11.9 MJ kg^{-1} for the treatment that received 130 kg N ha^{-1} fertiliser. This value corresponds well with the data from the Forage to Knowledge project, whereby the average ME recorded was slightly higher at 13 MJ kg^{-1} (AHDB, 2020). Once again, such differences in value reflect the agricultural system implemented, the grass species present in the sward, and variance in how the pastures are managed. We saw an increase in crude protein content following higher N fertiliser application in 2019. The results of this study are similar to that of Yu et al. (2011), who recorded changes in sward composition and a reduction in crude protein content in particular, along with an increase in litter and mosses percentages following a reduction in nutrient inputs to pasture over time.

4.2 Comparative nitrous oxide and carbon dioxide emissions

There was great variation in N_2O emissions between the treatments during the 2017 sampling period (Fig. 6). Both the control and the treatment that received lime and nutrients input produced relatively small N_2O fluxes throughout the sampling period. The results showed that reseeding led to higher N_2O emissions. This is also shown in other studies, e.g. Vellinga et al. (2004) found that increased tillage led to higher N_2O and CO_2 emissions in the Netherlands. Despite this, their study also highlights the importance of renovating pastures in the longer-term to prevent deterioration in pasture quality and hence, grass yield, which then necessitates the purchase of other feeds to fulfil the nutritional requirements of livestock. Here, we have a potential trade-off between managing the pasture to maintain grass growth and quality and the implications on N_2O emissions produced. Nevertheless, other multi-year studies that have directly measured the effect of ploughing and reseeding on N_2O emissions have also recorded decreased effect with time, with increased N_2O emissions only for several weeks, i.e. short-term emissions as opposed to a long-term effect (Merbold et al., 2014; Necpálová et al., 2013; Veltholf, 2010). The timing of renovating, and ploughing in particular, has been shown to impact N_2O flux measurements from intensively managed grassland, with increased direct N_2O emissions following autumn ploughing and reseeding as a result of ground-frost and freeze-thaw processes (Reinsch et al., 2018). Further research is required to determine whether the same trend apply for extensively managed grassland.

As previously mentioned, some studies have demonstrated greater N_2O emissions produced following ploughing compared to other grassland renovation techniques. However, our study recorded the highest N_2O emissions following rotovation; a cultivation practice that is not well studied. Ploughing buries the root layer, whereas rotovating disturbs and breaks up the topsoil layer, bringing root litter to the surface. In doing so, this may have led to increased mineralisation of the N pool in the upper soil, similar to other cultivation processes that lead to soil disturbance (Mutegi et al., 2010). Mutegi et al. (2010) also reported higher N_2O emissions following direct drilling and harrowing in comparison with conventional tillage in a winter barley field experiment. N_2O emissions from soils can vary substantially due to differences in soil type and cultivation dates. Ball et al. (2007) reported early spring as the most favourable period for ploughing organic pastures due to the moderately low temperature limiting N mineralisation in the soil, yet adequate N available and offtake for crop growth with increases in temperature later on in the spring.

Several studies have identified that changes in environmental conditions, such as rainfall, soil and air temperature can lead to strong temporal variability in N_2O emissions (Rochette et al., 2018; Butterbach-Bahl et al., 2013; Cantarel et al., 2012; Flechard et al., 2007). This could explain the lack of N_2O emission peaks from the treatments during the summer of 2018, with three split doses of N fertiliser applied to some of the treatments. Splitting N applications over the growing season, and therefore decreasing N rate, could reduce the risk of N_2O emissions as opposed to one large N application (Wang et al., 2016). However, Bell et al. (2016) reported that smaller, more frequent fertiliser applications led to greater N_2O emissions, although insignificant. Cumulative emissions of N_2O from the soil could also be greater due to a greater total N application rate (Bell et al., 2016). It is advised in the RB209 guide to reduce N application to swards in the event of a drought, due to restricted grass growth and hence poor N uptake by the plant (AHDB, 2017b). In the event of this occurring, N loss captured as N_2O emissions deriving from the soil would be minimal. Wang and Cai (2008) found that increased levels of soil moisture (100% water-holding capacity) led to greater N_2O emissions produced from arable soils applied N fertiliser than those with a lower soil moisture content. We saw similar trends in our study, N_2O fluxes produced were very low in 2018, when rainfall and soil moisture conditions were also low. This would also have had an impact on the EFs, with a high EF (2.26%) for one of the reseeded treatments in 2017 in comparison with the IPCC default for fertiliser applied to managed agricultural soils. However, the EF for the lime and fertiliser input only treatment was significantly lower than the default value (IPCC, 2019). In 2018, the EFs for all treatments were significantly lower than the IPCC default value of 1.6% and the uncertainty range, possibly due to the dry climate (Bell et al., 2015).

To our knowledge, there are no existing data on yield-scaled emissions, directly comparing N_2O emissions and grass production in relation to upland swards. The treatment that resulted in the largest yield-scaled emissions was the rotovated treatment. The smallest yield-scaled emission was from the lime and fertiliser only treatment. These results suggest that ploughing and rotovating were the greatest source of N_2O in 2017, while applying lime and fertiliser alone to permanent pasture was the most efficient option in terms of increasing grass production for the least N_2O emissions. However, further consideration should be given to wider potential GHGs associated with the lime and fertiliser treatment, such as the GHG emissions produced from the production of lime and fertiliser (FAO, 2017). It should also be noted that ongoing maintenance inputs of lime and fertiliser will be required to retain the productive capacity of improved swards. In addition, raising soil pH through lime application can facilitate the growth of N-fixing legumes such as clover in reseeds, thereby reducing reliance on chemical-N fertiliser inputs (Galbally et al., 2010), enhancing soil carbon sequestration (Puerta et al., 2018) and increasing the nutrient quality of pastures. This will reduce emissions associated with bought-in feed, and accelerating livestock performance (McAuliffe et al., 2018). Further work is necessary to explore how such broad potential impacts of reseeding impacts on the overall economic and environmental cost-benefits of pasture improvement. In addition, a better understanding of the other potential sources of N loss from upland pastures, and specifically from cattle systems in these areas (e.g. N_2O and ammonia (NH_3) from urine patches) is needed, to improve evidence-based policy decision making for the future of upland land use.

Recent guidance is available on the use of closed static chambers to determine N_2O fluxes (Charteris et al., 2020). Whilst some of the principles discussed in the literature will be applicable to monitoring CO_2 fluxes, there is limited current information solely focussing on the closed static chamber method for CO_2 flux measurements from grassland. Despite the fact that the closed static chamber methodology is commonly used as a simple technique for this purpose (Rochette et al., 1992), there is a concern that CO_2 fluxes are underestimated as a result of increased concentrations in the chamber headspace reaching a plateau after a certain period of chamber closure, based on a linear increase in CO_2 concentration (Heinemeyer and McNamara, 2011). Nevertheless, the results of the present study for the monitored CO_2 fluxes have largely indicated a linear increase in headspace concentrations in the chambers, and therefore dismisses this concern. Furthermore, the implementation of this technique in this study allowed for a seasonal cumulative CO_2 flux to be calculated (by integrating the flux over the monitored period). The closed dynamic chamber flux technique is an alternative and automated method commonly used to monitor CO_2 flux concentrations. Several previous studies have regularly monitored CO_2 fluxes within the first 24 hours post-cultivation via this technique (Álvaro-Fuentes et al., 2007; Willems et al., 2011). Contrary to the findings of others (Ogle et al., 2004; Reinsch et al., 2018; Smith et al., 2007; Vellinga et al., 2004; Willems et al., 2011), ploughing and rotovating prior to reseeding in our experiment did not lead to high CO_2 emissions from soil. Measurements for our experiment occurred an hour after ploughing and rotovating, and daily from then onwards. It is therefore possible that the peak fluxes could have occurred in between measurements within the first 24 hours, and the timings of these fluxes could be dependent on climatic variations, such as temperature and rainfall. Willems et al. (2011) monitored the effect of ploughing on CO_2 emissions from a brown earth soil and recorded a single brief CO_2 peak at 6.91 g CO_2 m^{-2} h^{-1} immediately after ploughing, followed by a rapid decline in CO_2 fluxes produced. This value is significantly higher than the greatest peak recorded in our experiment. However, the daily rainfall was far greater for their sampling season than that of ours in 2017, which was reflected in their results in that CO_2 emissions positively correlated with volumetric water content. In contrast, Yamulki and Jarvis (2002) observed greater CO_2 emissions from undisturbed pasture than ploughed land. Whilst that finding was observed following summer ploughing of long-term grassland sward as in our experiment, the technique differed in that the closed dynamic chamber methodology was implemented. Increased sampling frequency following treatment set-up and field operations as opposed to weekly sampling was deemed appropriate to improve the accuracy of the CO_2 flux measurements in the present study (Heinemeyer and McNamara, 2011).

A decline in soil pH from 2018 to 2019 suggests that the lime application in 2018 was ineffective. This was unexpected, as granulated lime is highly reactive and therefore, we hypothesised an increase in soil pH over the application years. However, the sampling period experienced abnormal weather conditions due to lack of rain in 2018. Fystro and Bakken (2005) observed an instant increase in soil pH in the top 25 mm of the soil following lime application. However, beyond this soil depth, changes in soil pH were dependent on site precipitation. It is therefore possible that poor soil moisture conditions due to low rainfall during the 2018 sampling period may have restricted the soil's ability to react to the lime applied in our study (Gibbons et al., 2014).

5. Conclusions

In conclusion we find that upland pasture grass production can be increased by ploughing, reseeding, rotavating and increasing inputs. However, many of these treatments also increase CO_2 and N_2O emissions measured both as total emissions and yield-scaled emissions. The most effective treatment in terms of increasing production while reducing yield-scaled emissions was increasing nutrient and lime inputs. This finding also suggests there is considerable scope for more efficient nutrient management in the uplands. The results demonstrate the importance of evaluating the agricultural system as a whole to ensure that linkages between pasture productivity and greenhouse gas emissions are fully considered when working towards improving upland pasture.

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Supplementary Material

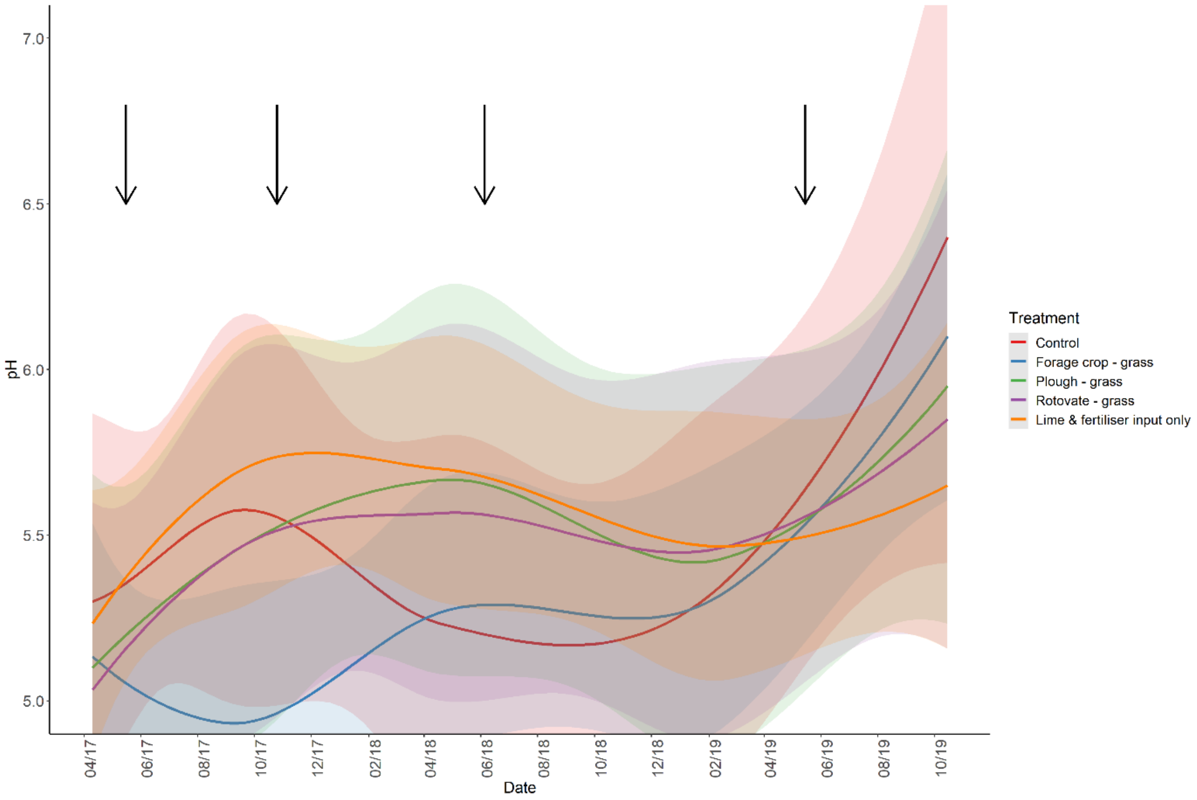

Fig. S1. Mean soil pH of the treatments for the sampling period (2017–2019). Coloured lines represent the treatment mean, shaded areas represent the upper and lower bounds of the SEM. Arrows represent the timing of lime applications.

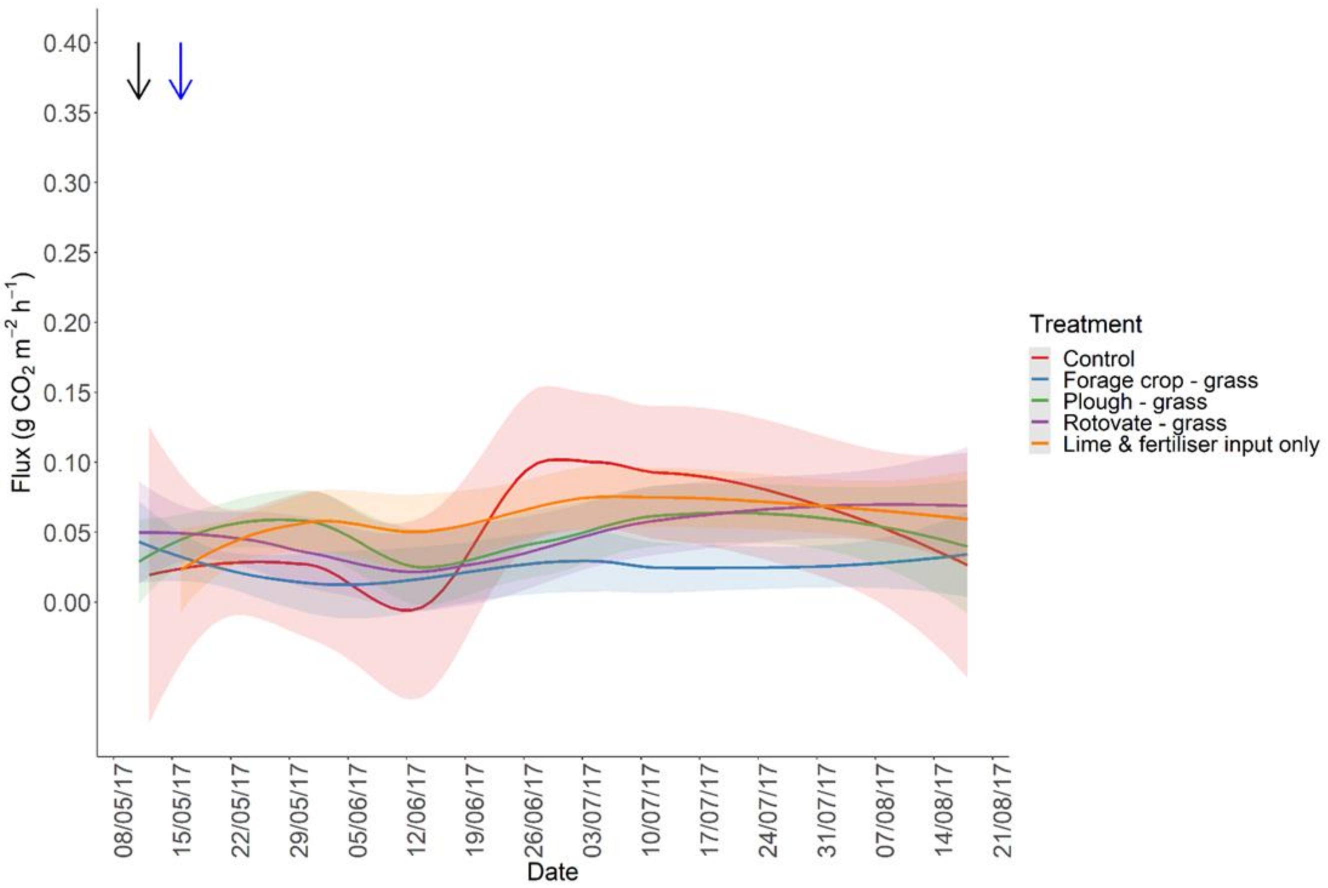

Fig. S2. Carbon dioxide (g CO_2 m^{-2} h^{-1}) emissions from the treatments in 2017. Coloured lines represent the treatment means (n = 3) and the shaded areas represent the upper and lower bounds of the SEM. Dates are in dd/mm/yy format. Amendments were made at the points of the arrows. The black arrow denotes the ploughing and rotovating and the blue arrow denotes the lime and fertiliser application. Shaded areas appear to exceed the minimum value on the *y*-axis due to the nature of the smoothing curve.

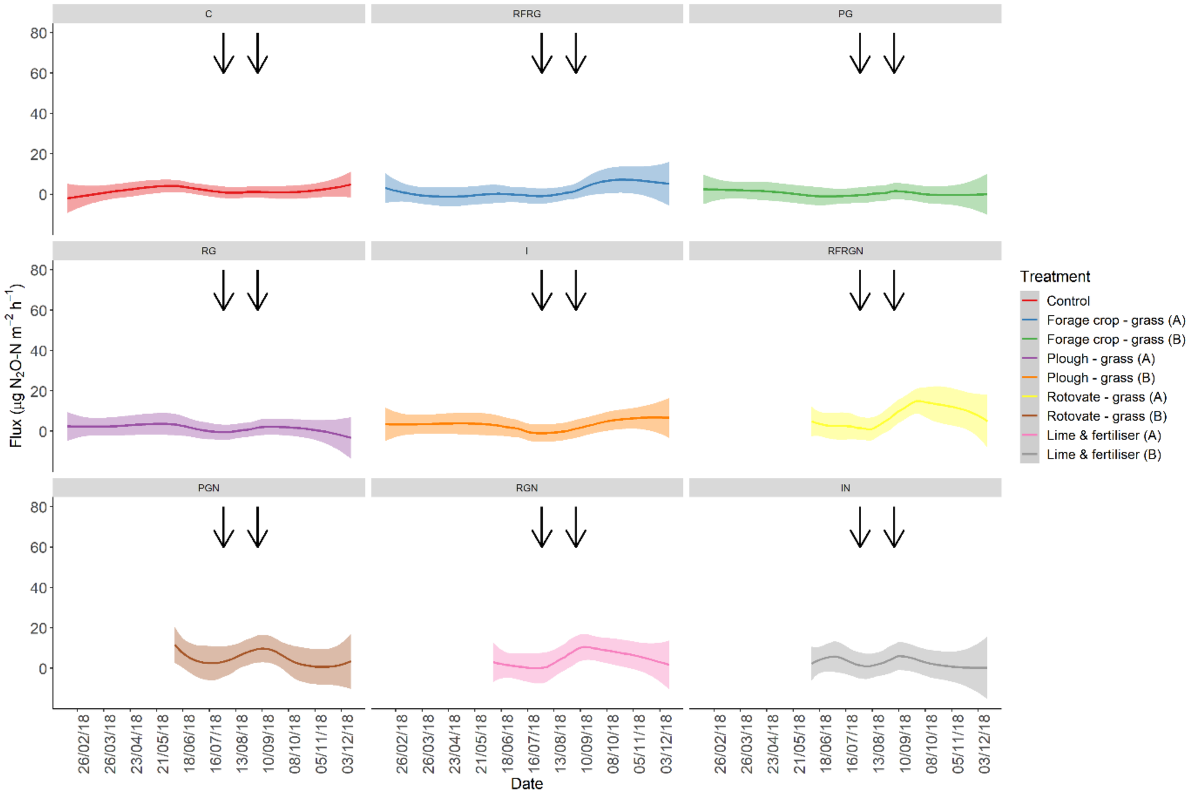

Fig. S3. Nitrous oxide (µg N_2O-N m^{-2} h^{-1}) emissions from the treatments in 2018. Arrows represent the timing of N fertiliser applications. N was applied to all treatments (control exempt) on 05/06/18. Second and third N applications were made to the required treatments on 31/07/18 and 05/09/18. Coloured lines represent the treatment means (n = 3) and the shaded areas represent the upper and lower bounds of the SEM. Variation in start date of curves is due to split-plotting.