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Optimizing farmyard manure and cattle slurry applications for intensively managed grasslands based on UK-DNDC model simulations

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Abstract

Fertilizer applications can enhance soil fertility, pasture growth and thereby increase~~ing~~ production. Nitrogen fertilizer has, however, been identified as a significant source of nitrous oxide (N_2O) emissions from agriculture if not used correctly and can thereby increase the environmental damage costs associated with agricultural production. The optimum use of organic fertilizers requires an improved understanding of nutrient cycles and their controls. Against this context, the objective of this research was to evaluate the scope for reducing N_2O emissions from grassland using a number of manure management practices including more frequent applications of smaller doses and different methods of application. We used a modified UK-DNDC model and

N_2O emissions from grasslands at Pwllpeiran (PW), UK, during the calibration period in autumn, were 1.35 kg N/ha/y (cattle slurry) and 0.95 kg N/ha/y (farmyard manure), and ~~while~~ 2.31 kg N/ha/y (cattle slurry) and 1.08 kg N/ha/y (farmyard manure) during the validation period in spring, compared to 1.43 kg N/ha/y (cattle slurry) and 0.29 kg N/ha/y (farmyard manure) during the spring at North Wyke (NW), UK. The modelling results suggested that the time period between fertilizer application and sample measurement (TPFA), rainfall and the daily average air temperature are key factors for N_2O emissions. Also, the emission factor (EF) varies spatio-temporally (0-2%) compared to the assumed uniform 1% EF used by the~~assumption of~~ IPCC. Predicted N_2O emissions were positively and linearly ($R^2 \approx 1$) related with N loadings under all scenarios. During the scenario analysis, the use of high frequency, low dose fertilizer applications compared to a single one off application was predicted to reduce N_2O peak fluxes and overall emissions for cattle slurry during the autumn and spring seasons at the PW and NW experimental sites by 17% and 15%, respectively. These results demonstrated that an optimised application regime using outputs from the modelling approach is a promising tool for supporting environmentally-friendly precision agriculture.

Keywords

UK-DNDC, emission factor, farmyard manure, greenhouse gases (GHG), nitrous oxide, cattle slurry

1. Introduction

Grazed grasslands provide us with food, biodiversity, and landscapes of high aesthetic quality, whilst also offering considerable potential to enhance carbon storage and watershed functioning

(Xu et al., 2019; Chianese et al., 2009). Grasslands and intensively managed pasture represent about 30% of the total global land use area and about 70% of the total agricultural expanse (Latham et al., 2014). Grazing livestock produce 33%–50% of global total agricultural gross domestic product (GDP) (Herrero et al., 2013). However, a number of challenges and risks exist for grazing ecosystems due to a range of interconnected factors including, climate change, excessive nutrient runoff, soil degradation, water shortages, changes in market demands, nitrous oxide (N_2O) emissions and over-grazing (Pulido et al., 2018; Thomas et al., 2018; Orr et al., 2016; Chen et al., 2008; Baral et al., 2014; Kim et al., 2014).

Agricultural soils contribute about 65% of global nitrous oxide (N_2O) emissions (Reay et al., 2012), and this greenhouse gas has a warming potential of approximately 300 times that of carbon dioxide (CO_2) over 100 years. In the UK, agriculture contributes up to 75% of N_2O emissions, of which 75% originate from agricultural soils following nitrogen fertilizer (both synthetic and organic) applications (Brown et al., 2016). In addition to the greenhouse effect, N_2O also plays an important role in ozone depletion (Smith, 2017). It has been reported that the contributions of organic fertilizer applications to N_2O emissions in the EU were approximately equal to 85% of synthetic fertilizers (Velthof et al., 2015).

Key components of grassland management include grazing intensity resulting from livestock stocking density and grazing regime, fertilization applications and, in some environmental settings, irrigation. Fertilizer inputs are important for pasture and forage productivity and corresponding livestock productivity (Bump and Baanante, 1996). However, fertilizer nitrogen can be a significant source of N_2O emissions from agriculture if not used correctly (Bodirsky et al., 2012). Furthermore, fertilizer use is very expensive in terms of both private and public costs. Optimized livestock production can reduce negative environmental impacts and assist adaptation to climate change if site-specific best management practices (BMP) are targeted to the four critical areas of on-farm nutrient management (source, rate, time and place) (Patil et al., 2018; Goulding et al., 2008). As a result, much effort has been made to assess the influence of inorganic and organic fertilizers on nutrient cycles, N_2O emissions and soil health (Bhogal et al., 2011; Evanylo et al., 2008; Patil et al., 2018; ,Li et al., 2013; Noirot- Cosson et al., 2017; Diego et al., 2017). For example, Pires et al., (2015) reported that the currently excessive use of N fertilizers not only decreases efficiency, but also increases the CO_2 concentrations in atmosphere. The optimum use of inputs using the 4R (Right source, Right rate, Right time, and Right place) principles will enhance the efficiency, reduce the emissions, and improve the economic conditions of those~~e~~ ~~persons~~ directly and indirectly attached with the farming sector. Lassaletta et al., (2014) concluded that more than half of the total N applied to ~~the~~ vegetation without following the 4R technique has~~is~~ no beneficial impact~~use~~ and subsequently degrades~~affects~~ the sustainability of land, air, and water resources over the~~on a~~ longer term~~s~~. Patil et al., (2018) showed that effective scheduling of organic fertilizers improves the quantity and quality of sunflowers compared to recommended traditional practices.

Organic fertilizer applications have potential benefits for grassland compared to synthetic fertilizers, including: (1) increasing soil organic matter; (2) improving soil quality; (3) producing organic foods, and; (4) increasing productivity (Zheng et al., 2010; Wang, 2014; FAO, 2017). Consequently, organic fertilizers, such as FYM and cattle slurry (CS), are increasingly applied in agriculture because of these wide-ranging benefits. However, organic fertilizers are more complex than synthetic fertilizers due to varying compositions, as evidenced, for example, by the substantial range in C/N ratios from 13 for FYM to 2 for cattle slurry (Bouwman et al., 1997; McTaggart et al., 1999; Akiyama et al., 2004; Green, 2015). Factors such as compositional variability mean that it is more challenging to optimize organic fertilization management in grasslands in terms of timing, frequency, and rates of application.

Process-based models, such as Denitrification and Decomposition (DNDC), can simulate the dynamics of nutrient cycles, soil carbon, and greenhouse gas (GHG) emissions for assisting the improved understanding of nitrogen cycles and their controls in grassland systems. DNDC can, for instance, help reduce the need for replicated laboratory and fi~~l~~eld experiments and optimize organic fertilizer management (Shen et al., 2018a; 2018b; Li et al., 1992; Yadav and Wang, 2017). Gilhespy et al., (2014) presented the different phases of DNDC development for taking into account integrated affects of soil, climate, vegetation type, management practices, and biogeochemical processes. Zhang and Niu (2016) reviewed the plant growth sub-model of DNDC. Shen et al. (2018a) modified the UK-DNDC model to analyse the effects of green compost and FYM applied on winter wheat and grasslands on N_2O fluxes at three UK research farms, whilst Shen et al., (2018b) studied N_2O emissions associated with slurry and digestate applications. The latter study reported that although organic fertilizers enhance soil fertility and crop yields, they have the potential to~~but might~~ increase N_2O emissions due to lower carbon and nitrogen ratios. While Shen et al. (2018a; 2018b) developed DNDC functions for new organic fertilizers, such as digestate and green compost, the effects of fertilization management and seasonality were not simulated at the study sites. Many studies have shown, nevertheless, that N_2O emissions can be affected significantly by fertilization management including type (inorganic, organic), application timing, application rate,~~,~~ method of application (Deng et al., 2016; Zhao et al., 2016), and environmental factors including seasonality. Therefore, there is a need for combining newly available field data and modelling tools, such as DNDC, to explore optimized organic fertilization management under site-specific combinations of climate, soil and grazing, as captured by existing UK research farms.

Because DNDC can be used for a Tier 3 approach to estimating the emission factors (EF) for N_2O, it has been widely used for simulations of annual N_2O emissions from various agricultural soils treated with CS and FYM, including accounting for spatial and temporal variabilities (Kim et al., 2013; Shen et al., 2018a,b). DNDC requires a range of input data including, for example, soil hydraulic, chemical property, vegetation, and climatic parameters. The simplified regression model for N_2O emission factors can therefore be a useful means of simplifying the data needs of process-based tools.

In this study, the overall aim was to evaluate the efficiency and impacts of fertilizer management, (i.e. manure application rate and split applications in grassland systems), on N_2O emissions. The research hypothesis was: split fertilizer applications according to crop physiological stages, as opposed to a one time application, can optimize farm management for reducing N_2O emissions. The specific objectives were: (1) to assess the effects of fertilizer management, in the form of more frequent doses and different application methods, on N_2O emissions in grasslands; (2) to simulate N_2O fluxes from two UK soils treated with FYM and CS fertilizers using the UK-DNDC model parameterised for specific soil, time between fertilizer application and measurement, and environmental factors, (3) to determine emission factors based on simulated N_2O emissions due to application of the two fertilizers to soils, and; (4) to develop a meta-model to explore the effects of climatic parameters (average daily temperature, precipitations) and the time interval (days) between fertilizer application and subsequent (different times) sample measurements (TPFA) on N_2O emissions.

2. Material and Methods

2.1. Research Sites

Two UK research sites were selected at Pwllpeiran (PW), Wales, and North Wyke (NW), England (Fig. 1) for sensitivity analysis of DNDC under different environment and management conditions. These two farms provide suitable datasets for two years (2011-2012) for representing variability in soil and climatic conditions (Nicholson et al., 2017; Cardenas et al., 2010; 2019; Orr et al., 2016). Table 1 summarises~~shows~~ the research site coordinates, soil physical and chemical properties, climatic data, manure application scheduling data, and crop type for different treatments during the autumn and spring at PW, and spring at NW. The treatments comprised a control, plus FYM and CS inputs using surface broadcasting (CS-SB), and CS application using a trailing shoe (CS-TS).

<Figure 1>

<Table 1>

The FYM is generated by beef cattle dung, urine, bedding material (such as straw) and uneaten forage, whereas the CS comprises dung, urine and includes rainwater if stored in an uncovered store (Pain and Menzi, 2011). The plants have immediate access to the small portion of N available in organic amendments;~~,~~ however, the remaining larger percentage of N is available after the decomposition of FYM. Irrigation water was not applied ~~D~~during the experimental periods at the two research farms. ~~, irrigation water was not applied.~~

2.2. The DNDC model

2.2.1. Model description

Li et al. (1992) developed the process-based DNDC model for simulation of GHG emissions (EPA, 1995) in the USA. DNDC is composed of ecological drivers (climate, soil, vegetation, and human activity) and soil environmental factors (temperature, moisture, pH, E_h, and substrates NH_4^+, NO_3^-, DOC after decomposition). The soil temperature and moisture profiles are determined by the soil and climate module. Depending on the soil and climatic conditions, the vegetation module of DNDC numerically simulates daily crop growth, nitrogen uptake, and root respiration. As a result, this module calculates biomass yields. The crop growth module is again composed of sub-routines for controlling management practices such as crop rotation, tilling, irrigation, fertilizer applications, and manure additions (Li et al., 1994). The decomposition module consists of four soil carbon pools for~~including~~ litter, microbial biomass, humads, and humus. This module simulates daily substrates (NH_4^+, NO_3^-, DOC) as a function of prevailing soil temperature and moisture.

The final module for nitrification and denitrification has~~ve~~ been improved using the concept of the anaerobic balloon, which swells and shrinks as a function of soil redox potential (Li et al., 2004). The substrates (such as DOC, NH_4^+ and NO_3^-) allocated to the anaerobic or aerobic compartments of each layer enable nitrification and denitrification processes to occur simultaneously.

For the current study, we used UK-DNDC because this version has been calibrated and validated under the UK-specific conditions for soil and climate combinations. In UK-DNDC, the soil is considered as a series of discrete horizontal layers ranging from 0-50 cm depth. Some soil properties (bulk density, porosity, hydraulic parameters) are assumed to be constant in each layer, but most of the soil properties (soil moisture, temperature, pH, field capacity, wilting point, carbon and nitrogen pools) can vary between layers. The model simulates dynamic variables for each layer for each time step. Since the observed data collected at the two study sites was measured at 10 cm soil depth, the model simulations were used to output predictions at the same depth.

2.2.2. Input parameters

Input parameters are daily weather data, soil physical and chemical properties, plants, and agricultural practices. Agricultural practices include tillage, fertilization, manuring, irrigation, and grazing/cutting. The soil parameters, including soil pH, SOC, NO_3^-, NH_4^+ for both study sites, are summarised in Table 1. The total N (kg-N/ha) contents in organic fertilizers for the CS-SB, CS-TS, and FYM treatments applied during the autumn and spring at PW and the spring at NW are also shown in Table 1.

Table 2 presents the nitrogen loadings for two fertilizers applied at the study sites, following the methods of Kim et al., (2013). The default C/N ratios were considered in DNDC to determine the carbon loading of FYM and CS treatments applied to the two study sites (Table 2). The term factor used in Table 2 shows the nitrogen loading according to Kim et al. (2013) for the reference case (factor = 1), 1.5 times the reference, and 2 times the reference.

Measurements of direct N_2O-N were made using 5 static chambers (0.8 m^2 total surface area) per plot over 12 months after manure applications. Gas samples were analysed by gas chromatography. The measured daily fluxes were regressed through linear gas accumulation. For further details, readers are referred to Chadwick et al. (2014) and Nicholson et al. (2017). Standard protocols were deployed for measuring soil moisture and soil temperature (Nicholson et al., 2017; Cardenas et al., 2010; Orr et al., 2016).

<Table 2>

For comparing and controlling the N_2O peak and overall annual emissions, CS was applied by two different methods, including one single time application and split applications according to the grass crop physiological stages (Moore et al., 1991) as shown in Table 3.

<Table 3>

As the soil at the two experimental sites is typically wet given the prevailing climatic conditions on the western side of the UK, UK-DNDC simulations assumed field capacity initially, with soil moisture varying from that point onwards as a function of soil and climatic parameter variability during the simulation period.

2.3. Emission factors for nitrous oxide

The emission factor (EF) is a measure of transformation proficiency of nitrogen available in fertilizer into N_2O emissions:

$$EF = \frac{N_2O_f - N_2O_c}{N_a} 100\% \qquad (1)$$

Where: N_2O_f is the total N_2O produced from the fertilized soils (kg N/ha/y);~~.~~ N_2O_c is the N_2O produced from the soil without application of fertilizer (kg N/ha/y), and~~;.~~ N_a is the total nitrogen (kg N/ha/y) available in the fertilizer applied to the soil.

The default EF fixed by IPCC Tier 1 is 0.01 (1%) and is related with N_2O emissions due to fertilizer applications to~~in~~ agricultural soils (Eggleston et al., 2006). The net emission flux, N_{net}, is strongly linear with N_a:~~.~~

$$N_{net} = EF \times N_a \qquad (2)$$

2.4. Statistical measures for UK-DNDC performance evaluation

The performance of UK-DNDC was evaluated using the observed N_2O emission data at the two UK sites. The ~~C~~coefficient of determination (R^2) and the root mean square error (RMSE) were~~are~~ used for testing model performance. ~~index of how well the modeled results reproduce observed data.~~ The relative error (RE) was~~is~~ used to compare approximations between the modeled results and the observed data:

$$R^2 = \frac{\left(\sum_{i=1}^{n}(S_i - S_{m,i})(O_i - O_{m,i})\right)^2}{\sum_{i=1}^{n}(S_i - S_{m,i})^2 (O_i - O_{m,i})^2} \qquad (3)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \tag{4}$$

$$\mathrm{RE} = \frac{O_i - S_i}{O_i} \tag{5}$$

Where: the subscripts *i* and *m* represent the index number and average value, respectively. The symbols *S* and *O* are UK-DNDC simulated and observed values, respectively. *n* is the total number of values. Based on the research objectives, statistical criteria for evaluating model performance were set as $R^2>0.5$, and average RMSE<0.5.

2.5. UK-DNDC calibration and validation

The UK-DNDC simulations were performed from 1 January to 31 December (Julian days) and annual (365 days) simulated and observed values were used to compare the cumulative N_2O emissions. The UK-DNDC model calibration was based on autumn and validation for spring at PW. The trapezoidal rule of interpolation was~~is~~ used to calculate the observed annual fluxes between measurement points.

The UK-DNDC model was tested against the datasets of water filled pore space (WFPS), soil temperature and N_2O emissions from the two study farms (Fig. 1). We firstly calibrated and validated the WFPS and soil temperature to calculate their correlation coefficient, R^2, (Eq. 3), *RSME* (Eq. 4) and *RE* (Eq. (5). (Fig. 2). Then, we calibrated and validated daily N_2O flux (Figs. 3, 4 and 5). We also calibrated annual N_2O emissions (Figs., 6 and 7). The best fitness parameters were obtained by finding the maximum coefficient of determination (R^2) and the minimum root mean square error, RMSE (%), through OFAT (one factor at a time) analysis. After calibration, the RMSE between annual observed and simulated values for N_2O emissions reduced from 2.7 (3.48 kg N/ha/y) to 1.51 (2.31 kg N/ha/y) in the case of the CS-SB treatment, and from 2.31 (3.49 kg N/ha/y) to 1.19 (2.33 kg N/ha/y) for CS-TS in the spring at PW. After calibration~~ed~~ and validation~~ed~~, UK-DNDC was used to simulate different rates of nitrogen loading to explore relationships between nitrogen loading and annual N_2O emissions under site-specific conditions and to explore optimal organic fertilizer applications and strategies in the two intensively managed grassland settings.

2.6. Nitrous oxide flux and a EF linear model

As there is a strong relationship between N_2O flux and N loading applied to agricultural soils, a linear regression model can be developed for reducing the input and calculation requirements (Cardenas et al., 2010).

$$w = aN + b \tag{6}$$

$$a = \frac{w(N) - w(control)}{N} = EF \tag{7}$$

Where: *w* and *N* represent the N_2O emission flux (kg N/ha/y) and nitrogen loading (kg N/ha/y), respectively. The slope "*a*" is equivalent to the EF and intercept "*b*" is the controlled emission flux (kg N/ha/y).

Although equation (6) is fit to describe the linear relationship on an annual basis, this relationship does not work on a daily time step due to the spatio-temporal variability of soil properties and climate change impacts (Laville et al., 2011).

3. Results and discussion

We examined the performance of UK-DNDC against the observed data for WFPS, soil temperature, and N_2O emissions at the two study sites. We subsequently performed scenario analyses to explore optimal timing~~,~~ and applications for organic fertilizers.

3.1. Daily WFPS and soil temperature

The UK-DNDC model simulates soil temperature based on WFPS (%) and soil hydraulic properties at a daily time step. Although the averaged observed event rainfall at both PW and NW is in the range of 7-10 mm, the variability of rainfall is different in terms of variance and standard deviation. This variability has an important influence on N_2O emissions. The simulated and observed WFPS (%) for both locations are in good agreement in terms of relative error (RE: 0.09-0.15) and RMSE (0.11-0.17), but the magnitude of the R^2 (0.12-0.27) is low (Fig. 2A). The reason for this relates to the irregular time intervals of the observed values. In the UK-DNDC model, the simulated values of WFPS are continuous and based on the previous time step value (Shen et al., 2018a). The model fit could be further improved by collecting continuous observed values, but this option is physically impossible. Fig.2B shows that the model captured the variations in soil temperature and matched the observed data well. However, the air temperature is slightly lower than the soil temperature due to being open to the atmosphere in both locations and climates. This can be explained by the fact that the UK-DNDC model simulates soil temperature and WFPS (%) using the thermos-hydraulic model at a daily time step. Because the heat transfer in soil is calculated using the Fourier law, the soil temperature is a balance between heat dissipation and soil heat capacity. When the heat capacity is larger than heat dissipation, the soil temperature could be slightly higher than the air temperature due to being open to the atmosphere in both locations and climates. Also, the continuous aerobic and anaerobic chemical reactions and subsequent heat transfer between soil layers is slow so more heat is kept in the soil, resulting in a warmer~~hotter~~ internal soil layer than the atmosphere.

<Figure 2A>

<Figure 2B>

3.2. Daily nitrous oxide fluxes

Fig. 3A shows the observed and simulated values for N_2O emissions for the four treatments including CS surface broadcasting (CS-SB, Fig. 3A(c)), CS trailing shoe (CS-TS, Fig. 3A(d)), and FYM (Fig. 3A(b)), plus the~~and~~ control treatment (Fig. 3A(a) for the autumn at PW. The simulated values of N_2O emissions follow the same trend of the observed values, but again the model fit is poor due to the irregular interval of the observed measurements. For~~In~~ the control and FYM treatments (Fig. 3A(a), 3A(b)), the magnitude of N2O emissions varied between 0-12 g-N/ha/d, but the treatments (Fig. 3A(c), 3A(d)) showed higher emission ranges between 0-80 g-N/ha/d. This greater magnitude is due to CS applications of 24 kg-N/ha in both treatments compared to the control. The FYM treatment received 131 kg-N/ha but the emission was in the same range as the control treatment, reflecting the fact that readily available nitrogen is only 0.9 kg/ha in FYM compared to 9.4 kg/ha for the CS treatments. For daily N_2O fluxes, CS holds more water than FYM. UK-DNDC generally over-predicts N_2O emissions. This could be due to poor representation of water factors in the denitrification process, in which the water is assumed to be constant. The N loading rates were low compared to typical applications. In the latter, the application rates normally vary between 200-250 kg N/ha for FYM and 150-400 kg-N/ha in the case of CS (Thomas and Hao, 2017; Kim et al., 2013). The lower application rates at the study sites reduced the N_2O emissions. The decision of whether to apply FYM or CS depends on the soil fertility status, crop N demand, and level of precision technology available for supporting field application. At the experimental sites, the soil fertility is relatively good and N demands are limited due to the prevalence of short root grassland compared with longer root crops; therefore, the application rates of CS and FYM are quite low compared to typical application rates reported more generally. At the experimental sites, the gradient of application rates was~~ere~~ used for a comparison of ~~among~~ lower and higher rates.

<Figure 3A>

Fig. 3B compares the observed and simulated values of N_2O emissions for the three treatments (CS-SB, CS-TS, and FYM) and control ~~treatment~~ for the spring at PW. The simulated values for

N_2O emissions follow the same trend of the observed values, but again the model fit was not good because of the irregular interval of observed measurements (TPFA). In the control and FYM treatment (Fig. 3B(a), 3B(b)), the magnitude of N_2O emissions varied between 0-20 g-N/ha/d, compared with the higher magnitude of between 0-130 g N/ha/d for the treatments (Fig. 3B(c), 3B(d)). This greater magnitude reflected the CS applications of 67 kg N/ha in both treatments. In contrast, the FYM treatment received a nitrogen application of 122 kg N/ha but the emissions were in the same range as the control ~~treatment~~, reflecting the fact that readily available nitrogen in FYM is only 0.5 kg/ha compared to 35 kg/ha for the CS treatments. Here, it is important to bear in mind that readily available nitrogen from manure is 5 times greater in spring compared to autumn since more intense and recurring rainfall allows for a greater magnitude of redox potential (E_h) and subsequently a higher magnitude of N_2O emissions.

<Figure 3B>

Fig. 3C compares the observed and simulated values of N_2O emissions for the three~~four~~ treatments and the~~including~~ control for the spring at NW. The magnitude of N_2O emissions varied between 0-20 g N/ha/d for the control, but between 0-200 g N/ha/d for the treatments. The latter reflected the CS applications of 77.4 kg-N/ha in both treatments. The FYM treatment received an application of 144 kg N/ha but the emission was in the same range as the control since readily available nitrogen in FYM is only 0.67 kg N/ha compared to 43.5 kg N/ha for the CS treatment. The readily available nitrogen in manure is 20% greater in spring at NW compared to spring at PW. As the N_2O emission depends on the rainfall intensity, initial soil moisture and temperature, application rate, timing, and frequency, the magnitude of simulated peak N_2O emission under the CS-SB and CS-TS treatments was greater (200 g N/ha/d) during the spring at NW than the magnitude (140 g N/ha/d) during the spring at PW. Furthermore, the rainfall during the spring at

PW is less intense and erratic compared to spring at NW. In the case of the FYM treatment during the spring at PW and NW, the average N_2O emission remains within 2-5 g N/ha/d, but the N_2O emission during the spring at PW (Fig. 3C) is more erratic than during spring at NW (Fig. 3C). This may be due to the erratic patterns of rainfall, soil temperature, and WFPS (%).

Regarding the mismatch between daily observed and simulated N_2O emissions, there are multiple reasons including the irregular intervals of the empirical data for soil WFPS and soil temperature and the impact of delayed bacterial activity due to daily corresponding temperature and/or rainfall events. During a specific day, the optimum range of soil WFPS and soil temperature favours biogeochemical processing due to nitrification and denitrification and subsequently N_2O emissions. The magnitude of emissions again depends on the fertilizer (organic/inorganic) rate. It means that if the soil WFPS and soil temperature are not within the optimum range, the bacterial activity slows down and results in an underestimation/ overestimation for the simulated N_2O emissions. Actually, the UK-DNDC model works well for annual emission fluxes (cumulative daily emissions), compared to daily emissions, due to the reasons mentioned above. Bearing the above in mind, the calibration and validation of annual emission fluxes under the different treatments, locations, and weather conditions, shows acceptable statistical performance (Table 4).

<Figure 3C>

Generally speaking, UK-DNDC generally over-predicts daily N_2O fluxes for the CS treatment.

The UK-DNDC model was calibrated by fitting the stress coefficient of manure (S_{mn}) in the main nitrifier and denitrifier equations, which are one of the main drivers for optimizing annual N_2O emissions and peaks. Table 4 presents the results for the calibration and validation periods at PW. The R^2 is above 0.5 under all treatments during autumn (calibration) and all treatments, except CS-TS, during spring (validation), which suggested that simulated and observed annual N_2O emissions were~~are~~ in good agreement. Similarly the RMSE was predicted to be below 0.62 (having R^2>0.5 in most cases) under all treatments during the autumn (calibration) and all treatments except CS-SB and CS-TS during spring (validation).

<Table 4>

3.3. Annual nitrous oxide emissions and emission factors

Many national and international reports, such as the annual IPCC report for~~of~~ GHGs report total emissions including seasonal and annual values rather than high resolution estimates. Therefore, UK-DNDC was also calibrated (during the autumn season at PW) and validated (during the spring season at PW) for annual N_2O emissions. Fig. 4 shows simulated and observed annual N_2O emissions under the CS-SB, CS-TS, and FYM treatments for the autumn and spring at PW and the spring at NW. The simulated emissions were relatively higher than the observed data in the case of the CS-SB (2.31 kg-N/ha/y versus observed 0.80 kg-N/ha/y), and CS-TS (2.33 kg-N/ha/y versus 1.20 kg-N/ha/y) treatments for spring at PW. In all other treatments, the model overestimated the annual emissions for the CS applications by 10-20% compared to the observed data, while it underestimated the emissions for FYM. This may be because the observed data is not available for the non-growth period in the winter and we used trapezoidal interpolation for the annual cumulative emissions, resulting in an overestimation bias.

The highest observed emission is from FYM for the autumn and spring seasons at PW (1.28 kg-N/ha/y, 1.277 kg-N/ha/y, respectively) due to the erratic rainfall patterns (Dobbie et al., 1999). The nitrogen loading (144 kg-N/ha/y) is greatest during the spring season at NW compared to autumn (131 kg-N/ha/y) and spring (122 kg-N/ha/y) at PW, but the erratic pattern of rainfall and WFPS at PW is more favourable than at NW. In addition, a higher soil pH value (>7) favours denitrification (Li et al., 1992), whereas a low pH (<5.6) strongly inhibits soil microbial nitrification and denitrification (Wang et al., 2013). The R^2 for the controls ~~treatments~~ ranged from 0.01 in the spring season at PW (Fig. 3B(a)) to 0.17 in the autumn season at PW (Fig. 3A(a)), while the R^2 for the ~~other~~ treatments ranged from 0.01 (CS-SB applied during the spring season at PW, (Fig. 3B(c)) to 0.17 (CS-SB applied during autumn season at PW, Fig. 3A(c)). Potential~~The~~ ~~R~~ reasons for the~~of~~ lower ~~value of~~ correlation coefficients for~~in~~ some treatments ~~can~~ include: (1) the daily N_2O emission is strongly correlated with corresponding daily temperature and rainfall (Giltrap et al., 2010)~~. It also~~ meanings that these climatic parameters are strong drivers of nitrous oxide emissions without depending on the measured day, and; (2) the bacterial activity is delayed for several days due to the ~~temperature and~~ rainfall events and corresponding temperatures but is then ~~and~~ stimulateds due to an increase in temperature.

The modelled N_2O fluxes treated with CS-SB and CS-TS for the autumn and spring seasons at PW and for the spring season at NW were higher than the observed values~~ones~~ (Fig. 6) because the modelled peak values were more numerous and higher (Fig. 3A©, 3A(d), 3B©, 3B(d), 3C©, 3C(d)), but the~~an~~ opposite trend was observed in the other treatments~~experiments~~ (Fig. 3A(b), 3B(b), 3C(b)) (i.e. the modelled N_2O fluxes for the spring and autumn seasons at PW treated with FYM, and for the spring season at NW treated with FYM were lower than the observed ones). The over and under predictions of observed annual N_2O emissions using the UK-DNDC model reflect the irregular intervals of observation, soil WFPS and the soil temperature status at a specific day and time.

<Figure 4>

Using eq.1 (Fig. 6) and modelled data, EFs for FYM and CS at the two sites were also calculated. The modelled EF exceeded the observed EFs except for the FYM treatment during the autumn and spring seasons at PW and the spring season at NW. The IPCC Tier 1 default (EF=1%) underestimated the observed EF (<1%) in all cases except the CS-SB treatment during the autu season at PW, and overestimated the simulated EFs (1% > EF <2%) for all cases except FYM during the autumn and spring seasons at PW and the spring season at NW. One of the reasons is that ~~the~~ some values of the observed emissions were negative (Fig. 3B, 3C), whereas modelled emission values produced by UK-DNDC were all positive (Myrgiotis et al., 2016). The ~~both~~ negative and positive values offset each other. Another reason is that, the UK-DNDC model produced many sharp and narrow peaks at low emissions in the case of the FYM treatment (Fig. 3A(b), 3B(b), 3C(b)), which contributed smaller percentages to the overall modelled emissions.

3.4. Effect of nitrogen loading rates on annual nitrous oxide emissions and EFs

Optimized fertilizer applications can mitigate N_2O emissions from grazing lands. N_2O emissions, with respect to fertilizer N input, depend on location, climate, crop type, fertilizer type, soil properties, N_2O emission measurement period, N input rates, biomass yield, cumulative N_2O emissions and the N_2O EF. Kim et al., (2013) applied four different levels of N inputs based on ~~the~~ 26 published datasets. These experimental sites were distributed globally in Canada, USA, and Europe. Their application rates on grassland are almost the same factor (1.5× and 2×). Therefore we used scenarios for FYM and CS by increasing by factors of 1.5 and 2 times the experimental loadings at the two study sites (Table 2) (Kim et al., 2013; Shen et al., 2018). The annual N_2O fluxes increased as a result of increasing the fertilizer loadings (CS and FYM) at both sites (Fig. 5). The response of the N_2O emissions as a function of nitrogen loading was similar in the case of CS-SB and CS-TS, as was~~nd~~ the gradual change (almost constant) due to the smaller percentage of readily available nitrogen in FYM compared to CS for the spring and autumn seasons at PW and the spring season at NW. The different scenarios of nitrogen loading forecasted the simulated emission fluxes and a regression model between nitrogen loading and emission fluxes was~~ere~~ developed (Eq. 6).

<Figure 5>

The fitted constants “a” and “b” for the scenario analysis and the corresponding linear lines are shown in Table 5 and Fig. 5, respectively. All of the coefficients of determination (R^2) exceeded 0.99 (Table 5), which indicates that the N_2O emissions increase linearly with increasing nitrogen loading. The projected constants (EFs) (Table 5) were much lower than 0.01 (1%) in most of the cases except the CS-SB and CS-TS treatments during the spring season at PW. The maximum EF was 2% for CS under the trailing shoe application method applied during the spring season at PW, and the minimum EF was 0.002% for FYM applied during the spring season at NW. The annual N_2O fluxes as a function of nitrogen loading are strongly ($R^2 \approx 1$) dependent on each other in all cases. For every 50 kg-N/ha/y of nitrogen loading, there was an increase of 0.5 kg-N/ha/y in the simulated annual N_2O emissions, which shows 1% emission flux in almost all cases except the FYM treatment, as shown in Figure 5. This response is due to the slower rate of degradation of FYM compared to CS.

<Table 5>

According to Kim et al., (2013), the relationship between N input and direct N_2O emissions follows three successive phases using the optimal N uptakes of both vegetation and soil microbes as boundaries. As N input initially increases (phase I), the N provided is consumed by plants and microbes, and N_2O emissions are primarily controlled by plant vs microbial competition for the available N. Therefore, in phase I, direct N_2O emissions increase linearly. Subsequently, as N additions exceed optimal N plant uptake rates, phase II would exhibit exponential increases of direct N2O emissions, since soil N_2O production increases rapidly with excess N supply. Finally, as N additions continue to increase progressively beyond the capacity of soil microbes to take up and utilize N (Phase III), the rate of N_2O production would slow down and reach a steady state. Accordingly, the N input ranges of phases I, II, and III may change. If the N input range of phase I is larger than the tested range of N input, it would appear to be a linear response of direct N_2O emission and N input as verified in Figure 5.~~ of the manuscript.~~ In contrast, if the N input range of phase I is smaller than the tested range of N input, an abrupt increase in direct N_2O emissions would occur inside the tested range of N input and it would appear as an exponential response of direct N_2O emissions with N input, as reported by~~fitted well by~~ Kim et al., (2013).

The optimal N uptakes of both vegetation and soil microbes may change depending on vegetation type, climate conditions (e.g. temperature, precipitation) and soil properties (e.g. Ph, redox potential, soil aeration, organic and mineral N, amount and availability of C, texture, mineralogy~~.~~). All these conditions used in this manuscript are different from those used in the study by Kim et al., (2013); therefore, regression models can be fitted well using both linear and non-linear models, depending on optimal N uptake by both vegetation and soil microbes at the locality in question.

3.5. Effects of N loading timing, dose and times on daily N_2O fluxes

Fig. 6 shows the correlation coefficients between observed annual N_2O emissions and three dynamic variables including TPFA, daily rainfall, and daily air temperature under the ~~three treatments, including~~ the control, CS, and FYM for autumn and spring at PW and spring at NW. The N_2O emissions occur~~s~~ due to the nitrification and denitrification processes, which are strongly related with these dynamic variables (Smith et al., 2003). The Arrhenius equation causes these chemical reactions to occur and N_2O emissions depend on temperature and soil aggregation (Smith et al., 2003). The variable WFPS does not take part directly in the reactions;~~,~~ however, the completion of these reactions depends on soluble substrates and oxygen as required by microorganisms. Under all cases~~treatments~~ (control, CS, and FYM), and for both the spring and autumn seasons at PW and the spring season at NW, the variable air temperature shows positive and rainfall negative correlation coefficients. ~~Whereas,~~ ~~t~~The third variable, TFPA, exhibited~~represents the~~ negative correlation under all treatments and seasons at both PW and NW. This shows that with the increase of TFPA, the soil N content will decrease, which is logical.~~ and makes sense.~~ Based on the positive and negative magnitude of correlation coefficients between~~of~~ TFPA, rainfall and temperature, it can be concluded that N_2O emissions at both research farms increases with the increase of temperature and decreases with the increase of magnitude of rainfall and TFPS.

<Figure 6>

3.6. Effect of scheduled and unscheduled fertilizer application on nitrous oxide emissions

The optimization of fertilizer input requires scheduled (split application during the growing season) and precise fertigation based on the required nitrogen in the soil under different crop physiological stages (Moore et al., 1996). These frequent but scheduled doses, according to the crop physiological stages, significantly reduce peaks and overall emissions compared to a one-time (unscheduled) application of fertilizer (Table 3). The optimum timing of organic fertilizer applications should not affect the silage quality, marginal profit, and grazing livestock. In order to quantify the reduction in peaks using both methods, the CS-TS treatment was selected for the autumn and spring seasons at PW and the spring season at NW (Fig. 7). The reason is that readily available nitrogen (RAN) in FYM is present in a smaller percentage compared to CS, which will take longer to degrade and be available to plants. The reduction in peak fluxes (schedule vs unscheduled) was 85% for the autumn season at PW (Fig. 7(a)) and 50% for spring at PW (Fig.

7(b)) and NW (Fig. 7(c)). The overall annual N_2O emissions (schedule vs unscheduled) decreased by 17% and 15% for the autumn season at PW and the spring season at NW, respectively (Lassaletta, 2014, Pires et al., 2015). On the other hand, these emissions can also show increases, such as an increase in~~of~~ overall annual emissions by 9% in the case of the spring season at PW. This makes sense as N_2O emissions are a function of air temperature, precipitation, and TPFA.

In practice, it is well realized that fertilizer best management practices (BMP) should utilize the 4R principle (Right source, Right rate, Right time, and Right place). This is embodied in Nutrient Stewardship addressing the right fertilizer source, at the right rate, the right time, and in the right place (IFA, 2007; Lassaletta et al., 2014; Wang et al., 2016). However, although at a first glance, this best management appears simple, it is, in fact, complex with respect to considering how to split nitrogen applications according to plant growth stages, especially in the context of ambient weather and soil conditions. Our results showed that NUE could be much improved by changing from low frequently split to high frequently split applications, such as changing from 1 time to 4 times. However, the corresponding improvement in NUE decreases if the frequency of split applications is even higher, as reported by Cardenas et al (2019). Cardenas et al., (2019) compared N_2O emissions associated with 4 split applications of inorganic fertilizers (AN320) with 6 split applications (AN320-split) (in their Fig. 4 and Table 2). However, it is important to note here that the times of the additional 2 applications were very close compared with the 4 time application scenario. Since both split application scenarios reported by Cardenas et al. (2019) were high frequency, their results did not show any significant effects of the number of split applications on N_2O emissions.

Atmospheric CO_2 enrichment could inhibit the assimilation of nitrate into organic nitrogen compounds (Bloom et al., 2010). The DNDC model takes into account the atmospheric background CO_2 concentration with a default value of 350 ppm, which affects plant photosynthesis. Also, according to Bloom et al., (2010), the concentration of CO_2 in the earth's atmosphere ranges between 280 and 390 ppm, which confirms that the default value used in DNDC is within this reported range. It is predicted that this concentration will reach between 530 and 970 ppm by the end of 21st century. Within this range of CO_2 concentrations, plant photosynthesis behaves normally and therefore, there is no significant impact on N_2O emissions. Of course, if this concentration doubles, as predicted by Bloom et al., (2010), the response of higher plants to a CO_2 doubling would be a decline in nitrogen status. Overall, this means that the frequency of split applications of organic/inorganic fertilizers according to crop physiological stages would likely decrease the emission rate and overall emissions (Reich et al., 2018).

Some comparisons between organic and inorganic sources of nitrogen showed the influence of fertilizer types on N_2O flux (Cardenas et al., 2019; Shen et al., 2018; 2020; Thomas and Hao, 2017). Cardenas et al., (2019) concluded that these emissions depend on the type and rate of N applied. For organic fertilizers, readily available nitrogen is much less than that reported for inorganic fertilizers; therefore, the emission rate, overall emission and emission factor (EF) is much lower than for inorganic fertilizers. Even within different forms of organic fertilizer such as cattle manure, digestate, and separated solids, the emission rate varies. For example, Thomas and Hao (2017) concluded that liquid biogas residues have a higher risk for N_2O emissions than both the separated solid fraction of the biogas residues and undigested cattle manure. Similarly, Shen et al., (2018; 2020) modelled N_2O emission following application of farmyard manure and green compost. The results showed that organic fertilizers applied to soils may increase nitrous oxide emissions due to their lower C/N rations, and therefore potentially contribute to global warming.

It was further concluded that N_2O emission is mainly related to air temperature, precipitation, as well as the time period between fertilizer application and sample measurement.

Keeping in view the reduction in peaks and overall emissions compared to one-time applications, it was concluded that scheduling compared to one-time applications per season (unscheduled) is an important factor for sustaining soil and water productivity, and reducing N_2O emissions for environmentally-friendly smart agriculture and for contributing to a climate change mitigation strategy. Therefore, our results are not in conflict with those reported by Cardenas et al.~~’s~~ (2019). Our results imply there is an optimal number of split applications. Our model can be helpful to determine additional nitrogen needs. Timeliness of application is essential to be sure plant yields do not suffer from nitrogen deficiency.

<Figure 7>

4. Conclusions

Organic fertilizers such as FYM and CS, are increasingly applied in agriculture because of the benefits they provide in terms of plant nutrients, and soil quality. However, the varying compositions of organic fertilizers, causes difficulties for precision fertilizer management. Therefore, it is still a challenge to plan organic fertilization, such as timing, frequency, and dose in site-specific conditions. In this study, the UK-DNDC model was applied to grazing grasslands treated with FYM, CS-SB, and CS-TS treatments typical of intensive grassland farming in the UK. The use of frequent low dose applications compared to one time amendments significantly reduced N_2O peaks, fluxes and overall emissions by 17% for CS-TS during autumn at PW and 15% for CS-TS during spring at NW, but increased emissions for CS-TS by 9% during spring at PW. It is therefore concluded that organic amendments scheduling compared to a traditional one-time application per season can be a useful on-farm mitigation measure for minimizing N_2O emissions.

The application of liquid manure in modern agriculture is one of the most important techniques for controlling overall N_2O emissions and fertilizer use efficiency, and this study demonstrates how the integration of empirical and modelling data can be used to help design the optimum use of farm organic manures and slurries.

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[#] both autumn and spring seasons at PW
[*]autumn season at PW (Source: Nicholson et al., 2017)
[**]spring season at PW (Source: Nicholson et al., 2017)
[$]spring season at NW (Source: Cardenas et al., 2010)

Table 2. Loadings of nitrogen and carbon applied to grassland under two different treatments (cattle slurry and farmyard manure) during autumn and spring at PW and spring at NW.

N and C loading by study site	**Treatment**					
	CS-SB*			**FYM***		
Autumn PW						
Factor	1	1.5	2	1	1.5	2
N loading (kg-N/ha/y)	24	36	48	131	196.5	262
C loading (kg-N/ha/y)	48	72	96	1703	2554.5	3406
Spring PW						
Factor	1	1.5	2	1	1.5	2
N loading (kg-N/ha/y)	67	100.5	134	122	183	244
C loading (kg-N/ha/y)	134	201	268	1586	2379	3172
Spring NW						
Factor	1	1.5	2	1	1.5	2
N loading (kg-N/ha/y)	77.4	116.1	154.8	144	216	288
C loading (kg-N/ha/y)	154.8	232.2	309.6	1872	2808	3744

Variable	**Site**	**Control**	**CS-SB**	**CS-TS**	**FYM**
Latitude	PW#	52.3526⁰ N	52.3526⁰ N	52.3526⁰ N	52.3526⁰ N
	NW	50.77035⁰ N	50.77035⁰ N	50.77035⁰ N	50.77035⁰ N
Longitude	PW#	3.7977⁰ W	3.7977⁰W	3.7977⁰ W	3.7977⁰ W
	NW	3.901072⁰ W	3.901072⁰ W	3.901072⁰ W	3.901072⁰ W
Soil texture		Clay loam	Clay loam	Clay loam	Clay loam
Clay (%)	PW#	28	28	28	28
	NW	29	29	29	29
Density (g/cm^3)	PW*	0.95	0.95	0.95	0.95
	PW**	0.9	0.9	0.9	0.9
	NW	0.68	0.68	0.68	0.68
Soil NO_3^- (mg/kg)	PW#	5.15	5.15	5.15	5.15
	NW	0.36	0.36	0.36	0.36
Soil NH_4^+ (mg/kg)	PW#	2.22	2.22	2.22	2.22
	NW	0.65	0.65	0.65	0.65
Organic C (%)	PW#	4.7	4.7	4.7	4.7
	NW	3.65	3.65	3.65	3.65
Soil pH	PW,NW	5.6	5.6	5.6	5.6
Ann. Rainfall (cm)	PW*	143	143	143	143
	PW**	203	203	203	203
	NW	148	148	148	148
Annual Ave.Temp. (⁰C)	PW*	9.88	9.88	9.88	9.88
	PW**	9.1	9.1	9.1	9.1
	NW$	10.21	10.21	10.21	10.21
Cropping		Grassland	Grassland	Grassland	Grassland
Manure. App. Rate(kg-N/ha)	PW*	0	24	24	131
	PW**	0	67	67	122
	NW	0	77.4	77.4	144
Date fertilized	PW*	NA	Sep 28,2011	Sep 28,2011	Sep 28,2011
	PW**	NA	May 2,2012	May 2,2012	May 2,2012
	NW	NA	Apr. 17,2012	Apr. 17,2012	Apr. 17,2012

*The default values of the C/N ratio for cattle slurry and farmyard manure are 2 and 13, respectively.
**The nitrogen loading factor was taken from~~has been used following~~ Kim et al., (2013).
PW-Pwllpeiran
NW-North Wyke

Table 3. Application of readily available nitrogen under the cattle slurry (CS) treatment in a single application and split applications (according to crop physiological stages) during autumn and spring at PW and spring at NW.

	Total RAN* kg N/ha	**Split1 kg N/ha**	**Split2 kg N/ha**	**Split3 kg N/ha**	**Split4 kg N/ha**
Autumn, PW	9.4	1.63	1.35	1.63	4.80
Application Date		April 5,2011	April 15,2011	April 30,2011	May 20,2011
Spring, PW	35	6.06	5.01	6.06	17.88
Application Date		April 5,2011	April 15,2011	April 30,2011	May 20,2011

Spring,NW	43.5	7.53	6.22	7.53	22.22
Application Date		May 12,2012	May 22,2012	07-Jun-12	29-Jun-12

* Readily available nitrogen

Table 4: Statistical measures including **c**oefficient of determination (R^2), root mean square error (RMSE), absolute error (AE), and relative error (RE), for comparing ~~between~~ observed and simulated annual nitrous oxide emissions under the different treatments during the calibration (autumn and spring at PW in 2011) and validation (spring at NW in 2012) periods.

	Control	**CS-SB***	**CS-TS****	**FYM*****
Autumn PW (Calibration)				
[a]Obs.N_2O	0.78	1.03	0.99	1.28
[a]Sim.N_2O	0.99	1.41	1.42	1.00
R^2	0.81	0.54	0.89	0.96
RMSE	0.24	0.48	0.62	0.61
AE[a]	0.22	0.39	0.53	0.54
RE(%)	28.04	37.47	43.27	-21.56
Spring PW (Validation)				
[a]Obs.N_2O	0.57	0.80	1.20	1.28
[a]Sim.N_2O	1.09	2.31	2.33	1.10
R^2	0.74	0.39	0.01	0.97
RMSE	0.60	1.52	1.18	0.42
AE[a]	0.52	1.51	1.13	0.29
RE(%)	91.65	188.28	93.81	-14.22

* cattle slurry treatment using surface broadcasting method
** cattle slurry treatment using trailing shoe method
*** farmyard manure
[a] Annual average nitrous oxide flux (kg-N/ha/y)

Table 5. The regression coefficients in equation (6) during the scenario analysis for nitrogen loadings under the cattle slurry surface broadcast (CS-SB), cattle slurry trailing shoe (CS-TS), and farmyard manure (FYM) treatments during the autumn season at PW, spring season at PW, and spring season at NW.

	CS-SB Autumn PW	**CS-TS**	**FYM**	**CS-SB Spring PW**	**CS-TS**	**FYM**	**CS-SB Spring NW**	**CS-TS**	**FYM**

a	0.0179	0.0182	8.00E-05	0.02	0.0204	3.E-05	0.0173	0.0174	2.E-05
b	0.9176	0.9208	0.9351	0.9616	0.952	1.0782	0.0899	0.078	0.2841
R^2	1	0.9998	0.9999	0.9998	0.9998	0.9966	0.9999	0.9999	0.9999

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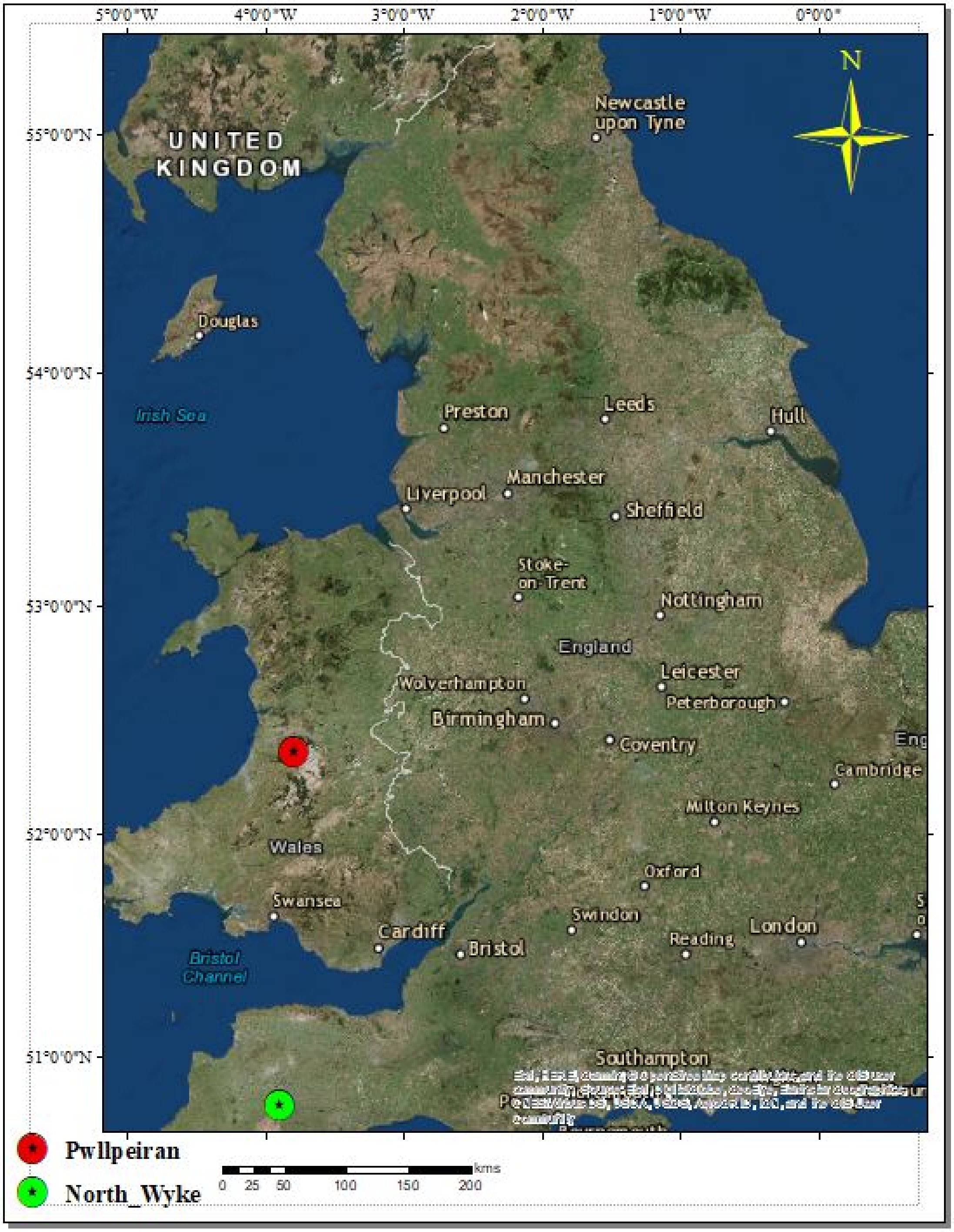

Figure 1. The locations of the two study farms in the UK.

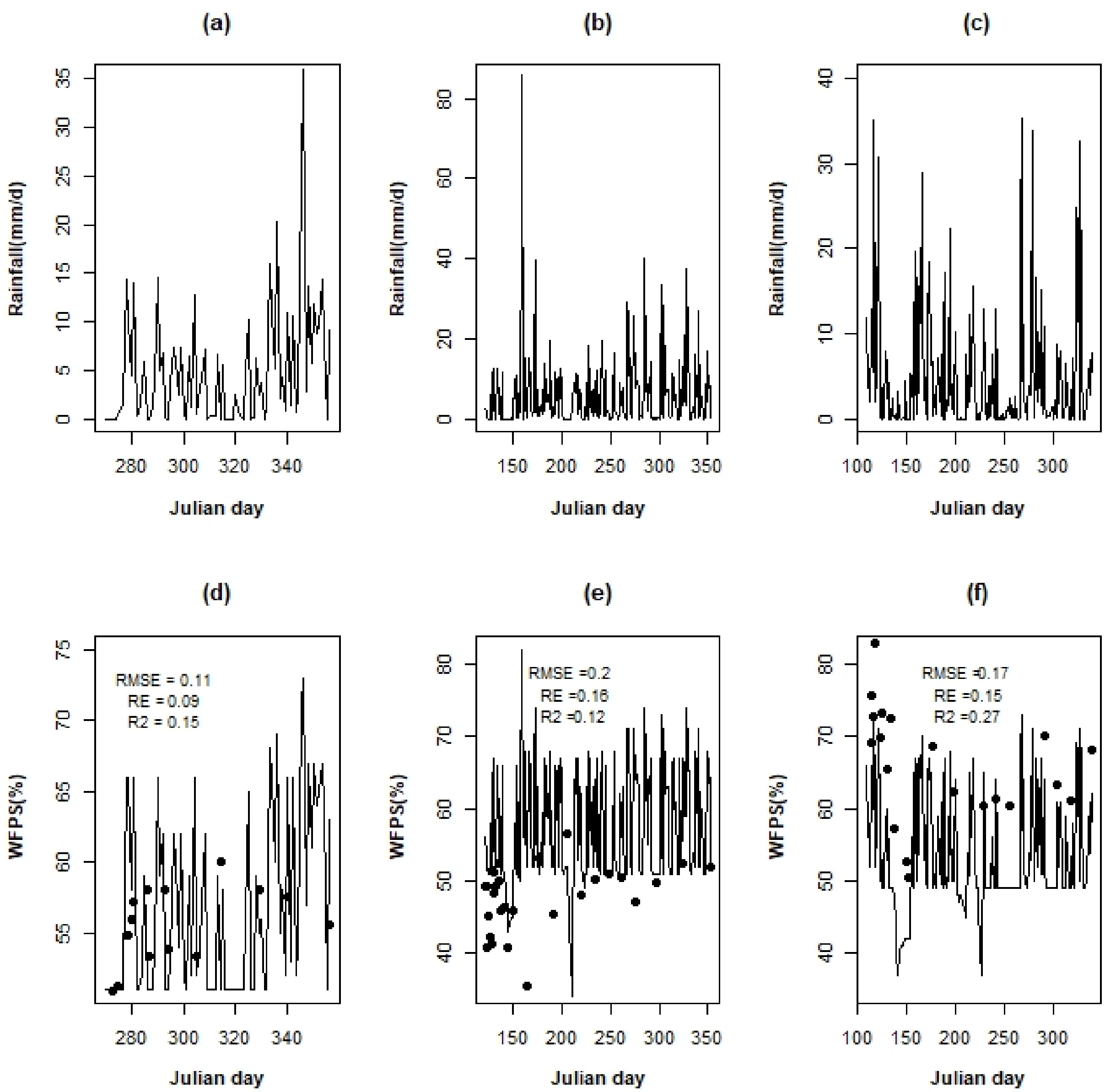

Figure 2A. Temporal variation of rainfall during autumn at PW (a), spring at PW (b), and spring at NW (c). ~~Similarly~~ ~~t~~Temporal variation of simulated (solid line) and observed (dots) WFPS (water filled pore space) during autumn at PW (d), spring at PW (e), and spring at NW (f).

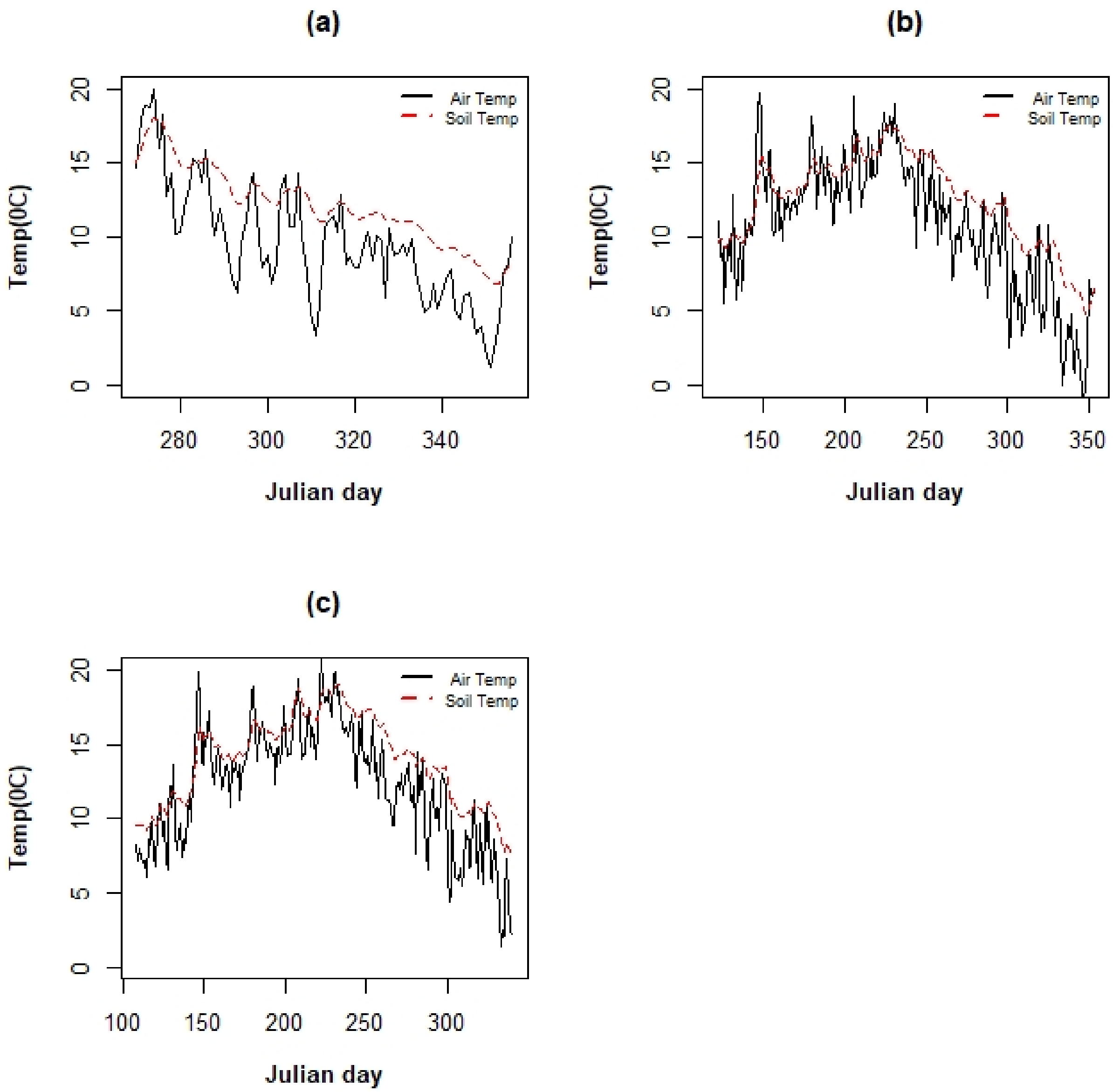

Figure 2B. Temporal variation of air and soil temperature during autumn at PW (a), spring at PW (b) and spring at NW (c).

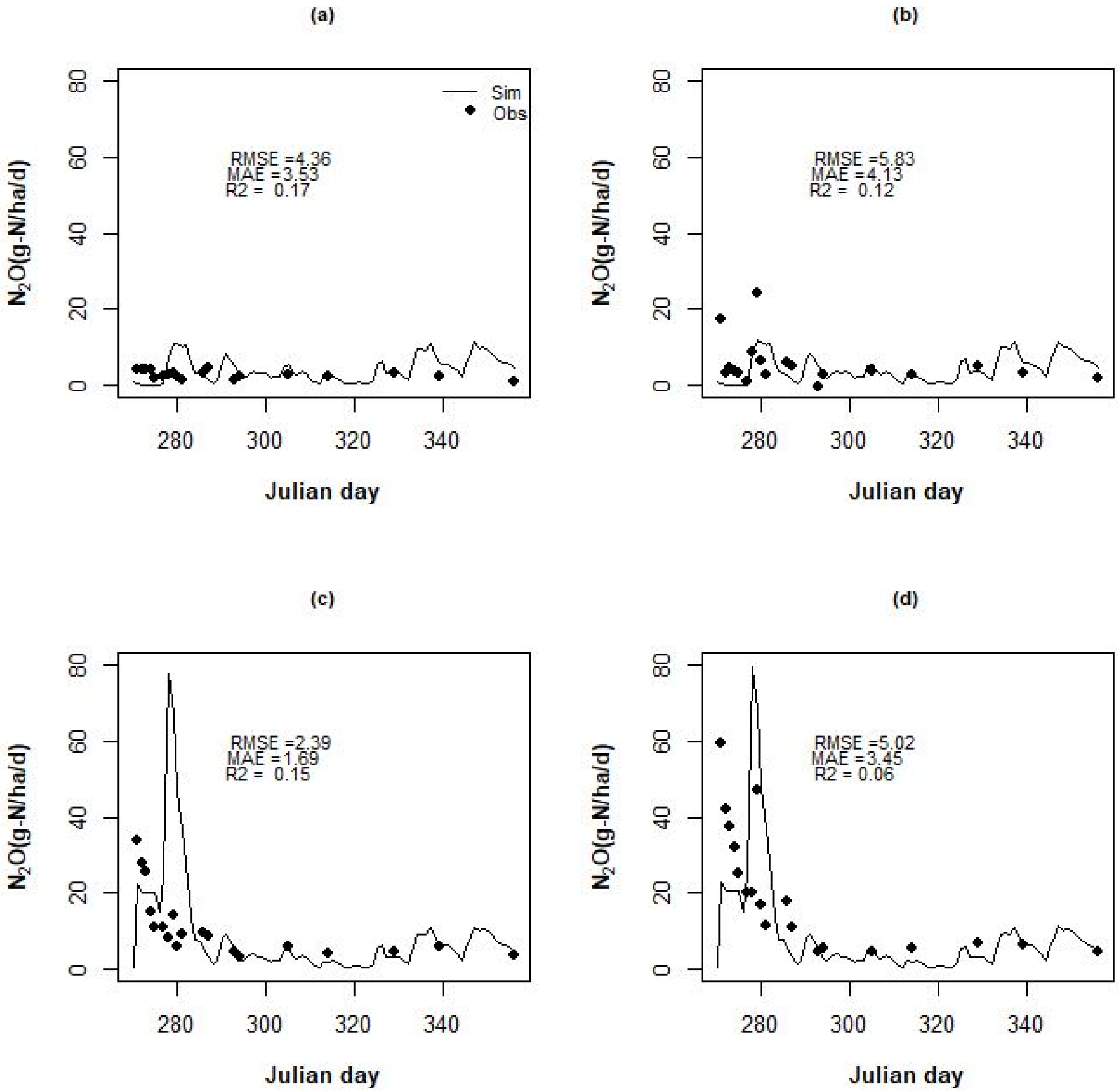

Figure 3A. Temporal variation of simulated (solid line) and observed (dots) nitrous oxide flux under the control (a), FYM (b), CS-SB (c), and CS-TS (d) treatments during autumn at PW. Here, FYM stands for farmyard manure, CS-SB for cattle slurry application using the surface broadcast method, and CS-TS for cattle slurry application using the trailing shoe method.

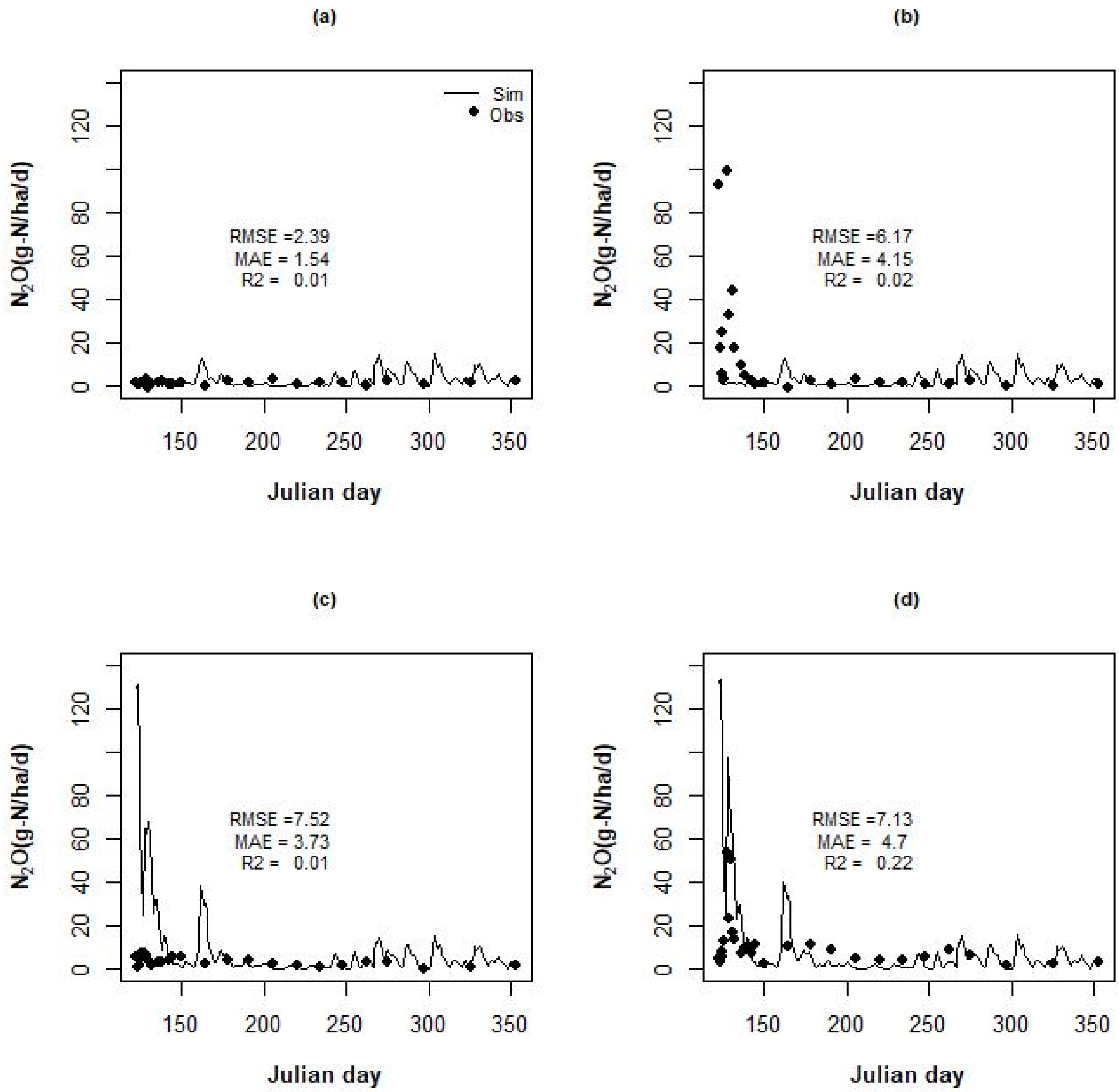

Figure 3B. Temporal variation of simulated (solid line) and observed (dots) nitrous oxide flux under the control (a), FYM (b), CS-SB (c), and CS-TS (d) treatments for spring at PW. Here, FYM stands for farmyard manure, CS-SB for cattle slurry application using the surface broadcast method, and CS-TS for cattle slurry application using the trailing shoe method.

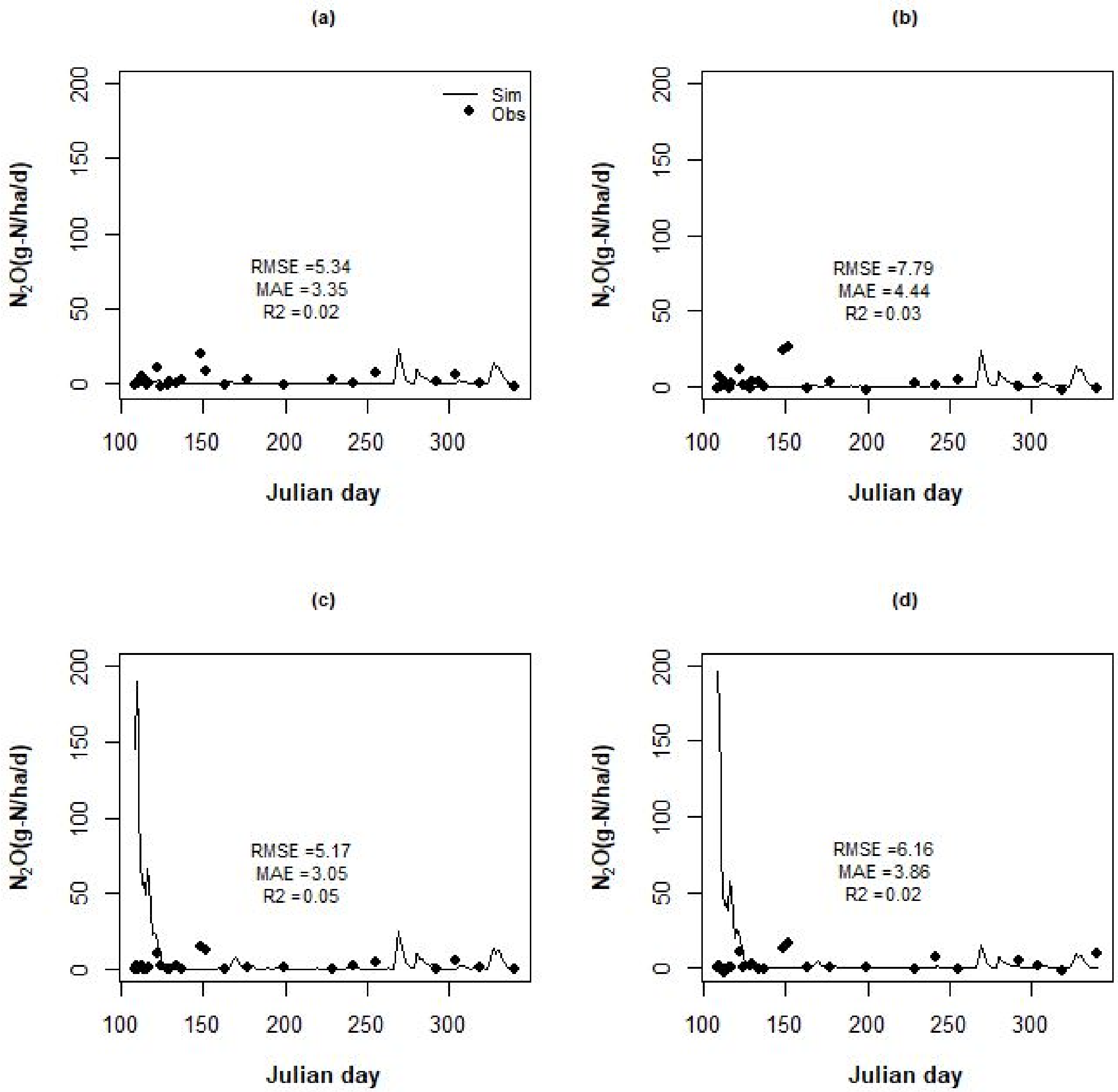

Figure 3C. Temporal variation of simulated (solid line) and observed (dots) nitrous oxide flux under the control (a), FYM (b), CS-SB (c), and CS-TS (d) treatments for spring at NW. Here, FYM stands for farmyard manure, CS-SB for cattle slurry application using the surface broadcast method, and CS-TS for cattle slurry application using the trailing shoe method.

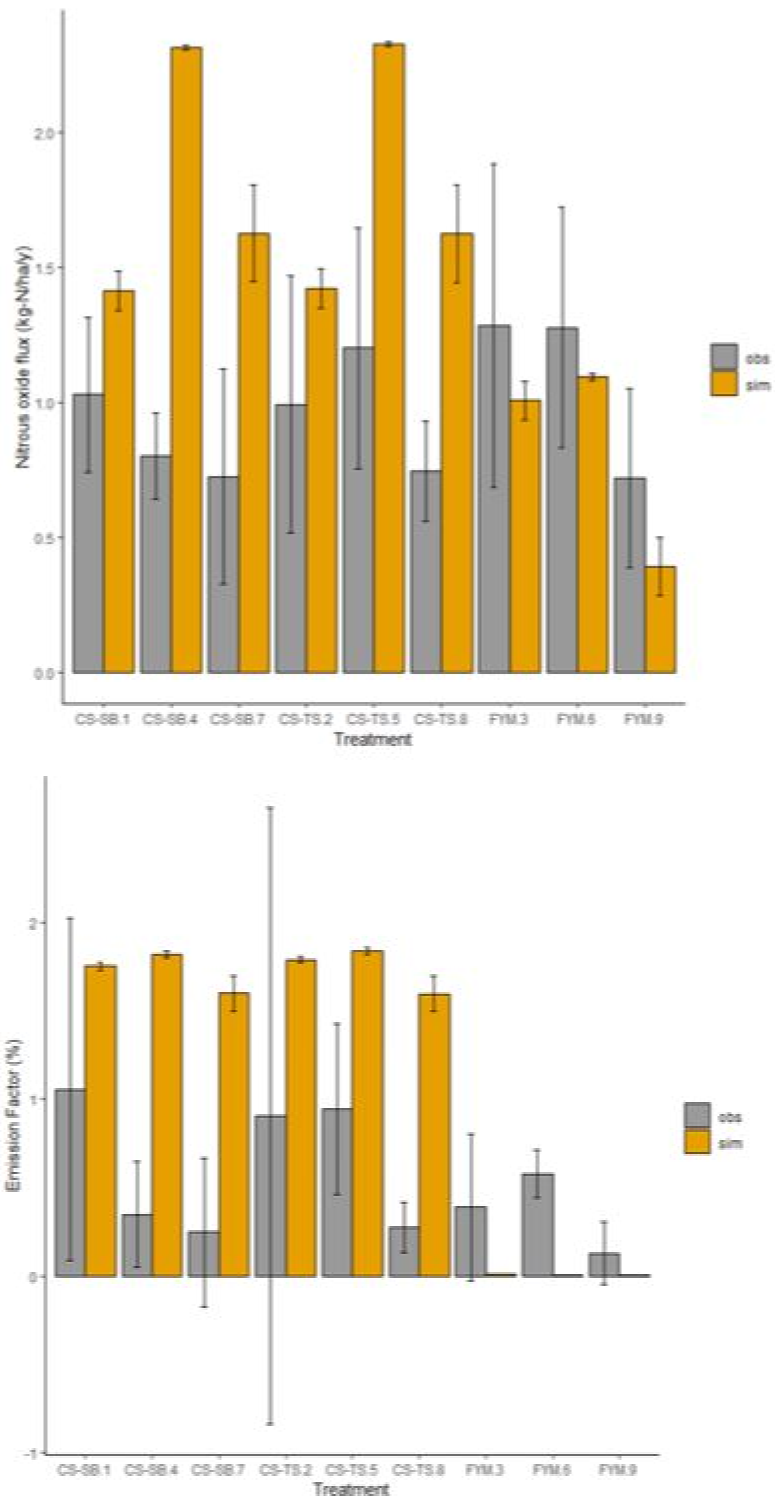

Figure 4: Observed and simulated annual nitrous oxide fluxes and emission factors (EFs) for the cattle slurry surface broadcast treatment (CS-SB) during the autumn (CS-SB1) and spring (CS-SB4) seasons at PW and the spring season (CS-SB7) at NW, ~~. F~~for the cattle slurry trailing shoe (CS-TS) treatment during the autumn (CS-TS2) and spring (CS-TS5) seasons at PW and the spring

season (CS-TS8) at NW and~~. Similarly~~ for the farmyard manure (FYM) treatment during the autumn (FYM3) and spring (FYM6) seasons at PW and the spring season (FYM9) at NW. The error bars indicate~~s~~ the standard deviations among replications of each treatment.

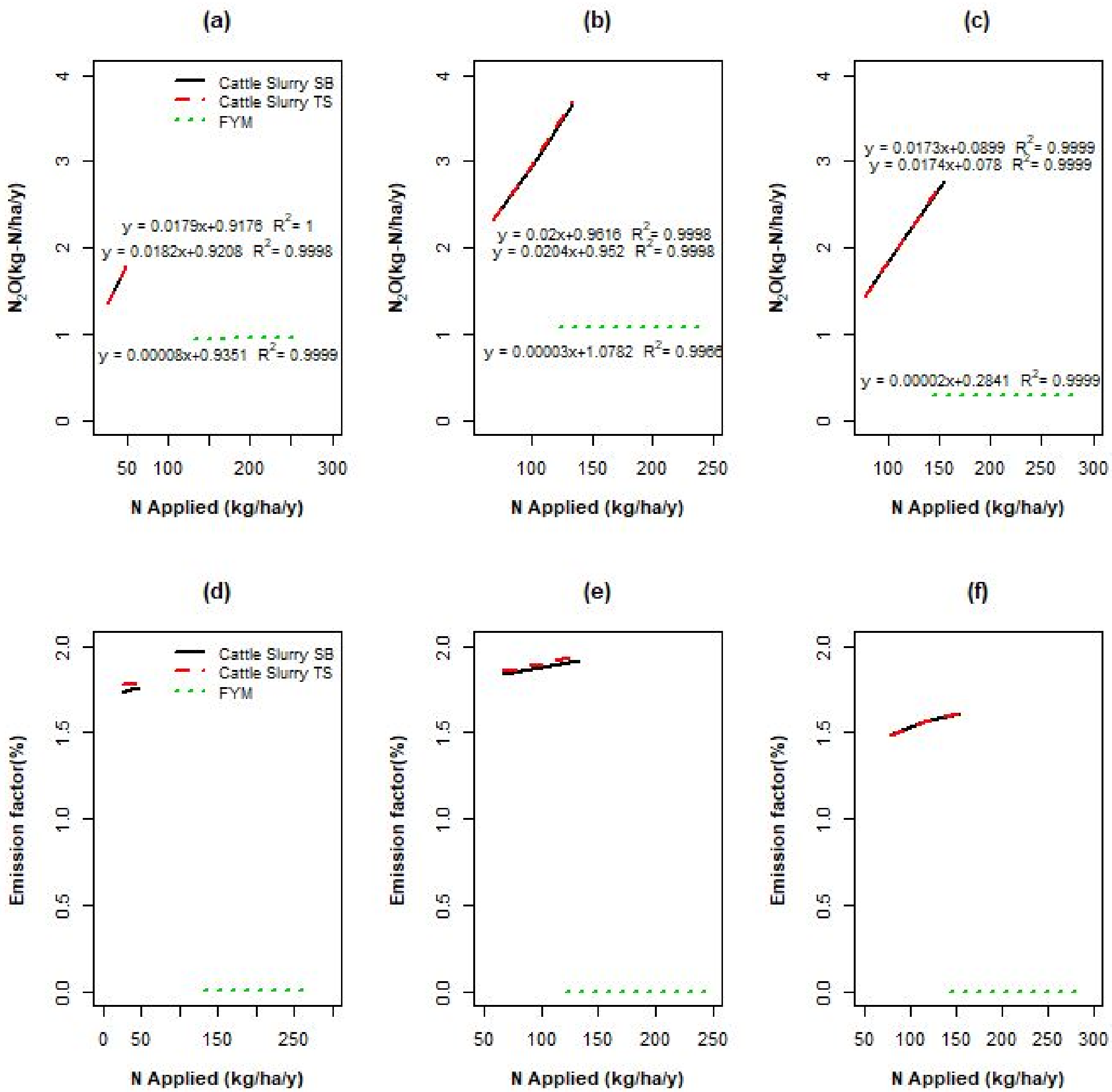

Figure 5: Predicted annual nitrous oxide fluxes with respect to increasing nitrogen loading under the cattle slurry surface broadcast (CS-SB), cattle slurry trailing shoe (CS-TS), and farmyard manure (FYM) treatments during the autumn at PW (a), spring at PW (b), and spring at NW (c). ~~Similarly c~~Corresponding emission factors (EFs) during the autumn at PW (d), spring at PW (e), and spring at NW (f).

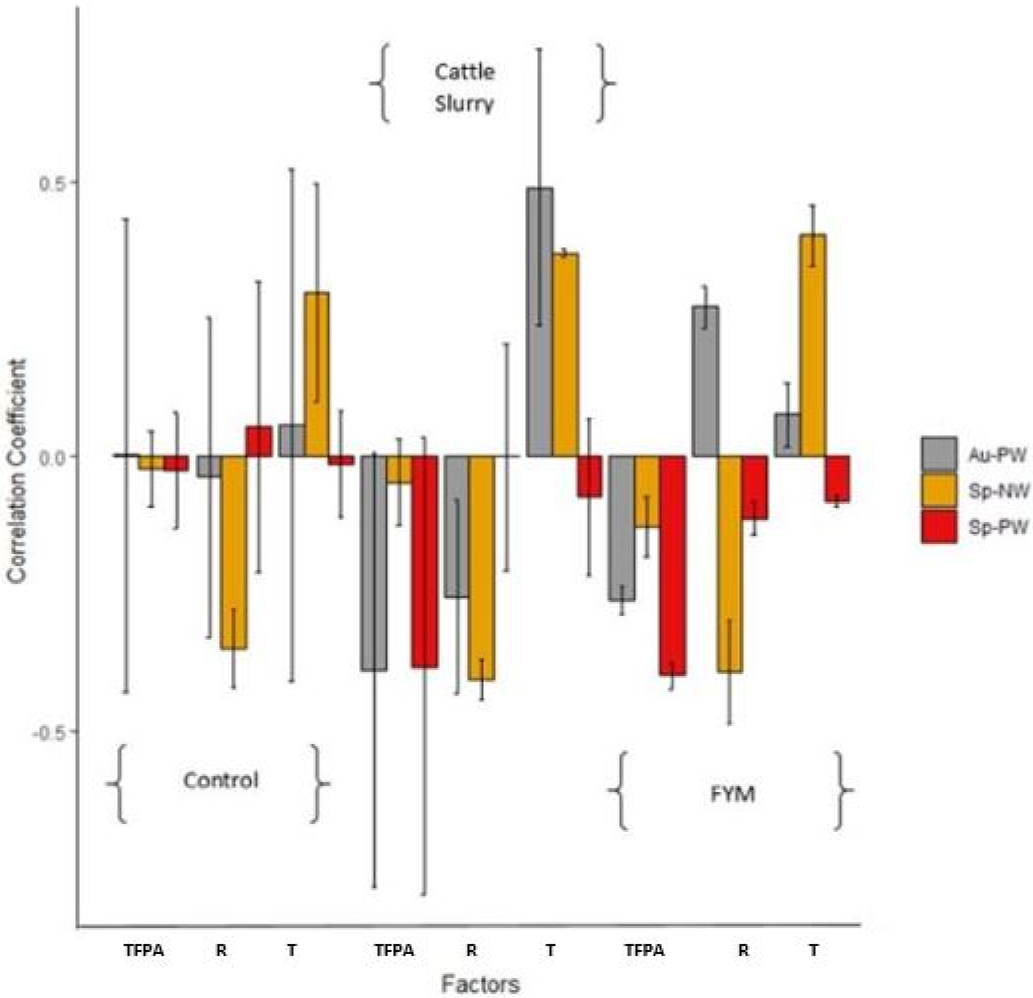

Figure 6: Linear correlation coefficients between~~of~~ the observed N_2O emissions and~~with~~ TPFA, rainfall (R), and average air temperature (T) under the control, cattle slurry and farmyard manure (FYM) treatments during the autumn at PW (Au-PW), spring at NW (Sp-NW), and the spring season at PW (Sp-PW).~~. Under cattle slurry treatment, the linear correlation between N_2O emissions and TPFA, R, and T. Similarly under farmyard manure (FYM) treatment the linear correlation between N_2O emissions and TPFA, R, and average air temperature.~~ The error bars indicate~~s~~ the standard deviation among replications of each treatment.

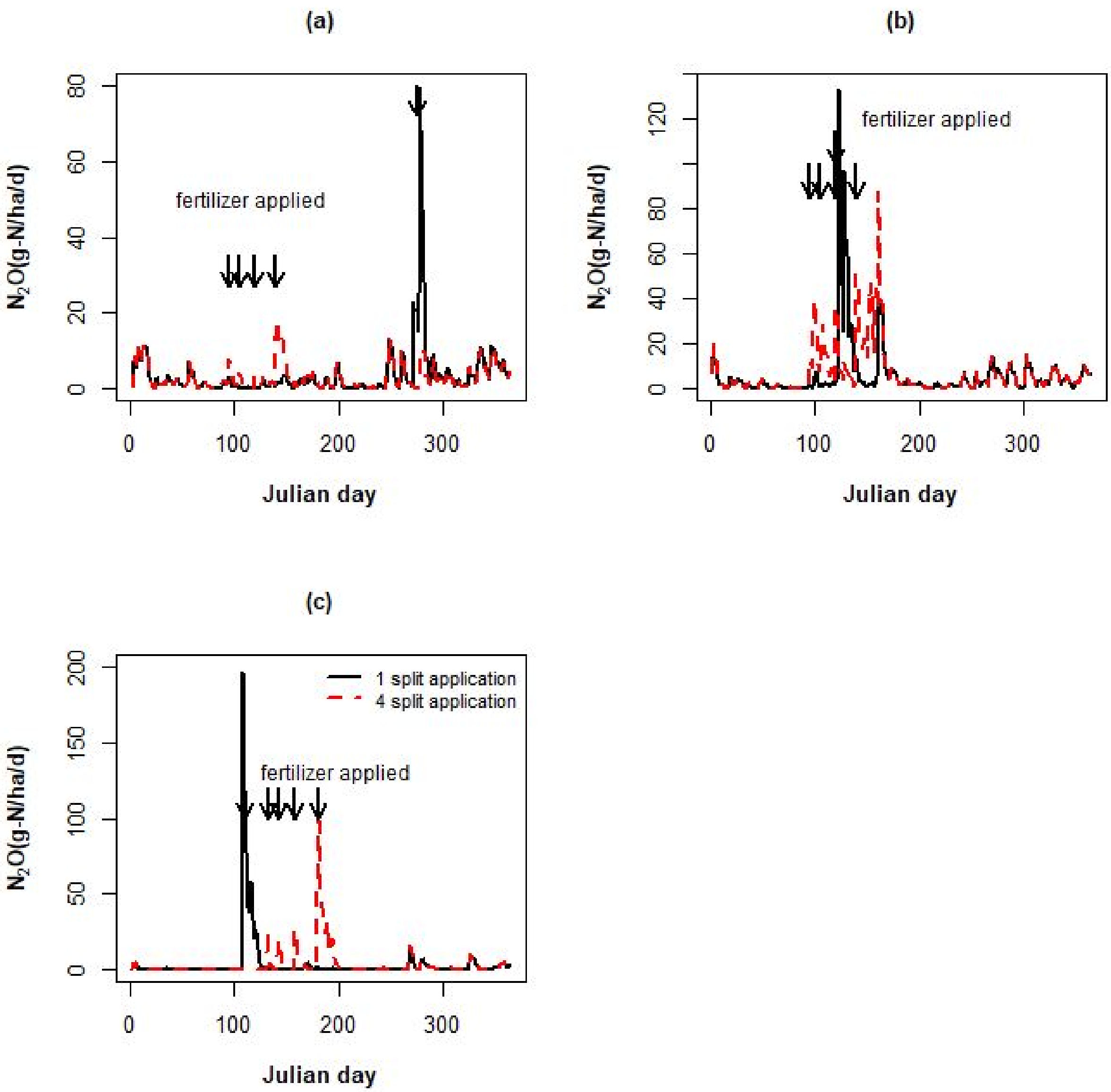

Figure 7: Comparison of nitrous oxide fluctuations after one time ~~split~~ (black line) and four times split (red line) ~~split~~ organic fertilizer applications under the cattle slurry treatment during the autumn at PW (a), spring at PW (b), and spring at NW (c).