Rothamsted Repository Download

A - Papers appearing in refereed journals

Shepherd, A., Hartman, M. D., Fitton, N., Horrocks, C. A., Dunn, R., Hastings, A. and Cardenas, L. M. 2019. Metrics of biomass, live-weight gain and nitrogen loss of ryegrass sheep pasture in the 21st century. *Science of the Total Environment.*

Metrics of biomass, live-weight gain and nitrogen loss of ryegrass sheep pasture in the 21st century

Anita Shepherd, Melannie D. Hartman, Nuala Fitton, Claire A. Horrocks, Robert M. Dunn, Astley Hastings, Laura M. Cardenas

PII: S0048-9697(19)32049-2
DOI: https://doi.org/10.1016/j.scitotenv.2019.05.038
Reference: STOTEN 32199

To appear in: *Science of the Total Environment*

Received date: 18 March 2019
Revised date: 28 April 2019
Accepted date: 3 May 2019

Please cite this article as: A. Shepherd, M.D. Hartman, N. Fitton, et al., Metrics of biomass, live-weight gain and nitrogen loss of ryegrass sheep pasture in the 21st century, Science of the Total Environment, https://doi.org/10.1016/j.scitotenv.2019.05.038

Metrics of biomass, live-weight gain and nitrogen loss of ryegrass sheep pasture in the 21st century

Anita Shepherd[a], Melannie D. Hartman[b], Nuala Fitton[c],

Claire A. Horrocks[a], Robert M. Dunn[a], Astley Hastings[c], Laura M. Cardenas[a]

[a] Sustainable Soil & Grassland Systems, Rothamsted Research, North Wyke, Devon, EX20 2SB, United Kingdom

[b] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, CO 80523-1499 USA

[c] Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St. Machar Drive, Aberdeen, Scotland, AB24 3UU

[1] Corresponding author anita.shepherd@abdn.ac.uk, tel. +44 1330 882434

Melannie D. Hartman, melannie.hartman@colostate.edu

Nuala Fitton, n.fitton@abdn.ac.uk

Claire A. Horrocks, claire.horrocks@rothamsted.ac.uk

Robert M. Dunn, robert.dunn@rothamsted.ac.uk

Laura M. Cardenas, laura.cardenas@rothamsted.ac.uk

Astley Hastings, astley.hastings@abdn.ac.uk

[1] Present address: Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, Scotland, AB24 3UU

Abstract

This study argues that several metrics are necessary to build up a picture of yield gain and nitrogen losses for ryegrass sheep pastures. Metrics of resource use efficiency, nitrous oxide emission factor, leached and emitted nitrogen per unit product are used to encompass yield gain and losses relating to nitrogen. These metrics are calculated from field system simulations using the DAYCENT model, validated from field sensor measurements and observations relating to crop yield, fertilizer applied, ammonium in soil and nitrate in soil and water, nitrous oxide and soil moisture. Three ryegrass pastures with traditional management for sheep grazing and silage are studied. As expected, the metrics between long-term ryegrass swards in this study are not very dissimilar. Slight differences between simulations of different field systems likely result from varying soil bulk density, as revealed by a sensitivity analysis applied to DAYCENT. The field with the highest resource use efficiency was also the field with the lowest leached inorganic nitrogen per unit product, and vice versa. Field system simulation using climate projections indicates an increase in nitrogen loss to water and air, with a corresponding increase in biomass. If we simulate both nitrogen loss by leaching and by gaseous emission, we obtain a fuller picture. Under climate projections, the field with the lowest determined nitrous oxide emissions factor, had a relatively high leached nitrogen per product amongst the three fields. When management differences were investigated, the amount of nitrous oxide per unit biomass was found to be significantly higher for an annual management of grazing only, than a silage harvest plus grazing, likely relating to the increased period of livestock on pasture. This work emphasizes how several metrics validated by auto-sampled data provide a measure of nitrogen loss, efficiency and best management practise.

1. Introduction

1.1 Food Production and Sustainable Management

Agricultural production needs to increase to feed an increasing global population under a changing climate. Strategies that promote long-term sustainability and yields, rather than purely peak quantity, should be introduced (Heinemann et al., 2013). Unsustainable farming practises run the risk of environmental pollution due to nutrient run-off, soil degradation and the loss of biodiversity through inappropriate management (Tilman et al., 2002; Hayarti et al, 2010). Nitrogen (N) fertilizer increases crop production, but a large proportion of agricultural N is leached to the environment in chemical forms that have caused contamination of drinking water and eutrophication of water bodies (Diaz and Rosenberg, 2008, EPA Science Advisory Board, 2011) and its gaseous emission is the form of nitrous oxide participates in photochemical reactions in the upper atmosphere (the stratosphere) that destroy ozone (Crutzen 1970).

Improving one aspect of the field system, does not always have a beneficial effect on other environmental features. A test of beneficial and harmful effects, or gains against losses, can be viewed by using metrics to compare management methods, and innovations could be compared to a baseline of traditional agronomy to compare benefits and offsets. Many agricultural metrics exist, however there is no consensus on a correct or most suitable one. Hayati et al. (2010) advise to construct metrics which are location specific and within the context of the situation. Our interest in this study is to view how several related metrics can improve agronomic information.

1.2 Comparative resource use and productivity

N use efficiency (NUE) can be measured in different ways, as crop N offtake per unit of N applied, or as defined by Moll et al. (1982) as grain production per unit of N available in the soil, thereby translating it to a measure of biomass per unit N applied. Resource use efficiency (RUE) is a ratio of productivity per unit of resource (Sheriff et al., 1995) where the resource can be any limiting factor to growth. If the resource is soil N, the definition of RUE overlaps that of Moll's definition of NUE, and these metrics on traditional management can act as a benchmark from which future improvements can be assessed. Low values usually indicate inefficient use of the added N whereas very high values usually indicate the mining of soil N (Norton et al., 2015). NUE is not necessarily a direct quantitative estimate of N loss from the system, because N not removed in the harvest might remain in the soil. Over the long term, however, changes in soil N stocks are usually low relative to inputs and outputs, and therefore, low NUE values over multiple years are reasonably reliable indirect indicators of probable significant N loss to the environment (Norton et al., 2015).

RUEs relating to productivity are important agronomic indicators focussing on production as the aim rather than efficient use of the N. An advantage of RUE relating to productivity and fertilizer is that the biomass and fertilizer data are generally available at the field level. In this study RUE is used, and termed f-RUE (fertilizer RUE).

1.3 Leached N

Plant available N loss depends upon a balance of the timing and rate of N application and the demand for N by the crop, or by microbial uptake. If uptake has a lower rate than application, or heavy rains follow application, excess NO_3^- and NH_4^+ is susceptible to water transport. NO_3^- flows through soil pores more rapidly than NH_4^+ which is held back by chemical bonding (Mekala and Nambi, 2016). Nitrate is a common risk in leached runoff to water bodies, due to the tendency of eutrophication to result in reduced oxygen in water, detrimental to aquatic and human life. In this study, we refer to leached inorganic N, predominantly NO_3^-, as leached N because dissolved organic N cannot be automatically sensed in runoff like inorganic N, due to the need to digest the sample prior to analysis which is not possible to automate under field conditions (ASA Analytics, 2017). Studies in agriculture have generally shown less leaching from dissolved organic N than inorganic N (Siemens and Kaupenjohann, 2002; Lehmann et al., 2003), but we accept that the lack of measured dissolved organic N measurement is a gap in the system.

1.4 N_2O emissions

Agriculture practices of N amendments cultivation, excess soil water, can increase N_2O production and emissions (Del Grosso, 2006). Mineral N supply, plant N demand, and abiotic soil conditions interact to control N_2O emissions from soils. Agricultural practices also increase NO_3^- leaching, which enters aquatic systems or is transported to a non-farm plant-soil system, and undergoes denitrification which results in indirect N_2O emissions.

To reduce leaching losses, best practise field management tries to minimize the amount of excess nitrate (NO_3^-) present in the soil at any given time, timing the application of fertilizer to smaller and more frequent applications. However, the fact that pores hold back ammonium (NH_4^+), allows it to be in contact with microbial matter longer (Mekala and Nambi, 2016). This increases the risk of conversion from NH_4^+ to nitrite and then to NO_3^- by nitrifying bacteria in aerobic conditions, and then conversion to N_2O by heterotrophic bacteria in anaerobic conditions. Both aerobic and anaerobic processes result in the production of N_2O, a potent greenhouse gas and precursor of stratospheric ozone loss. These processes occur simultaneously and in proximity in grassland soils (Abbasi & Adams, 1998).

1.5 Agronomic modelling as a precursor to metric calculation

Data collected manually, or by sensor, is not available every day for every year, and weather cannot be measured for future climate projections. The only way to obtain consistent multi-annual production and N loss data is to simulate the data using a calibrated model. We have chosen the DAYCENT model (Parton et al., 1998) for its applicability to our study. This is a field-scale model concerning soil emissions, leaching and crop production, which calculates the grazed offtake of biomass, from which we determine the live-weight gain efficiency of livestock.

2. Aim of Study

Our aim is to view how collating several related metrics, related to the gains or losses of nitrogen in traditional agronomic practises, can build up information on the agronomic system. This is carried out across three neighbouring sheep pastures under a similar soil type, and the same historic climate and projected late 21st century climate, where the main difference is the seasonal pasture management.

We will use measured variables from manual soil sampling and air and water quantity and quality sensors of the North Wyke Farm Platform (NWFP) site to calibrate and validate the DAYCENT agricultural systems model. The calibrated model will provide information to calculate the metrics concerned with field-scale gains in production against losses of N. Three fields will be compared under two types of traditional annual management, grazed use only and a silage crop followed by grazing. A null hypothesis is that the two types of management result in the same yield gain to nitrogen loss.

3. Materials and Methods

3.1 Site description

The NWFP (Orr et al., 2016) is the grassland research site of Rothamsted Research (50.46.30 deg. N–3.54.54 deg. E, 150 m a.s.l.). It is located at North Wyke in the south-west of England to the north of Dartmoor National Park, the largest area of upland in south-west England, and the sheep pastures are typical of those found in the south-west region. The NWFP fields in this study are located on clay loams of the Halstow soil series.

In this study we are interested in three specific fields of the NWFP, Longlands South, Dairy North and Golden Rove (Fig. 1). Since 2011, fields of the NWFP have been made into hydrologically sealed units, on which the fluxes of soil water are measured. The fields drain naturally to a clay subsoil of low permeability below 30 cm depth. Runoff leaving individual fields flows into surrounding drainage ditches and is channelled to a flume. Surface flow cannot be measured separately from lateral flow, so the term runoff comprises all field water flow to the flume. The flume is fully instrumented to enable flow rates to be measured and water samples to be automatically collected and analysed. Runoff flow is measured in litres per second at 15 minute intervals, measured at a V-notch ceramic weir with connection to a Teledyne ISCO 4230 bubbler flow meter. The flume measurements are converted from level of water to flow rate. In addition, a Nitratax instrument measures NO_3^- in runoff flow. Fifteen-minute interval data were scaled up to the daily time-step of the DAYCENT model, and used for runoff validation. Adcon SM1 capacitance soil moisture sensors are located in the centre of NWFP fields at 10, 20 and 30 cm depth. All sensor data is telemetried to a server. Manual sampling is taken to measure silage crop harvest yields, soil NH_4^+ and NO_3^-, and N_2O by chamber measurements.

The three study fields are all sheep pastures maintained with ryegrass (*Lolium perenne*). Each year, these fields are either grazed, or have one crop grown for silage and grazed after harvesting, silage harvest years can be seen in Tables 2 and 3. Replicate samples (four samples per field on four dates) were taken at periods during the growing seasons of 2013 and 2014 for soil NH_4^+ and NO_3^-, and N_2O emissions (measured by 12 automated chambers on each field, periodically moved to different locations to cover different areas). In a modelling study such as this, we have to use historic data, because we are trying to match sensor data with manual soil nitrogen sampling campaigns, and it was the manual soil NH_4^+ and NO_3^- sampling which was most limited.

3.2.1 DAYCENT model set-up

DAYCENT (Parton et al., 1998) is an agricultural system model simulating crop growth and biogeochemical cycling between the soil-water-crop-atmosphere. Plant production is a function of genetic potential, phenology, nutrient availability, water/temperature stress, and solar radiation. The model includes soil organic matter decomposition pools (active, slow and passive) with different decomposition rates, above and belowground litter pools and a surface microbial pool. Soil NO_3^- and NH_4^+, labile soil carbon, water content and temperature determine N_2O production (Parton, 1998). DAYCENT was used because it has been globally validated against forage production (Henderson et al., 2015). It was chosen because of its flexibility, many field management techniques are simulated and linked to the system, and it incorporates forage removal and nitrogen return by ruminants. It was also chosen for ease of use and applicability to our study; it has a daily time-step and a scheduling file which controls the simulation, bringing together all input files and process modules. Organic matter decomposition, nitrification, denitrification, water balance and nutrient transport are included in the model. The model is able to simulate the soil water, soil NO_3^- and NH_4^+, crop yield, leached N and separate outputs for daily N-gas flux (N_2O from nitrification, N_2O from denitrification, NO_x, N_2). Whilst all these variables are necessary for validation crop-soil nitrogen-water-atmosphere processes of the grassland system, it is the crop yield, leached N and N_2O that are especially pertinent to this study.

This work was carried out using the model version listed as ‘DailyDaycent_August2014’, an update to the downloadable version 4.5 of DAYCENT, in terms of crop growth and soil pools. A climate record (1982-2016) was provided from the central weather station located on the NWFP (station domain DLY3208 DEVON, Met Office).

The properties of the soil in the three fields (bulk density, pH, % sand, % clay, organic matter content, field capacity and permanent wilting point) were based on NWFP field surveys conducted on the pastures of Longlands South, Dairy North and Golden Rove in 2012 (Table 1). Agronomic management data was converted into scientific units from the farm management records from the open-access NWFP data portal (https://nwfp.rothamsted.ac.uk/), summarized in Table 2. Fertilizer applied was converted into elemental units using the fertilizer handbook RB209 (Defra, 2010).

A moderate grazing regime was selected in the model’s grazing management options, which simulated a linear decrease in production through the growing season, involving the offtake of 40% of biomass as live shoots and 10% of biomass as leaf litter. In the case of sheep grazing, the management option was set to return 90% of N in offtake to the soil, and proportion 34% of excreted N into faeces, the rest in urine. It is advised (Eblex, 2016) that the percentage of live biomass grazed is normally 50% or above, hence this was increased by 50% but this resulted in no difference in model output of N in soil, leached or emitted.

DAYCENT allows the creation of new management options, to create tailored effects of each type of management. We created new grazing options to switch grazing on and off for the exact dates when livestock were in the field. The option to switch on grazing simulation requires fraction of biomass grazed and fraction of N returned, so these were set to zero and this module listed in the model's scheduling file to switch off the grazing. New fertilizer options have been created, each new fertilizer type and application rate requires a value containing specific rates of N applied, calculated from different formulations and spreading rates using RB209 recommendations. Each fertilizer module has a different name and each one is listed as required in the scheduling file to set up an application.

Two schedule files were created: a spin-up file of grazed grassland without inorganic fertilizer for years 1 – 1900 to balance biogeochemical cycling, leading on to the main schedule file for years 1901 - 2016. Using a spin-up output for initialization of the main simulation, is commonly utilized with DAYCENT to represent the historic land use and management of the site and initialize soil organic matter pools before current practices are simulated. Our focus is the period 2011-2015, for which we have very detailed field management operational data records for type, rate and dates of fertilizer application, number of days of sheep grazing, dates of harvest, from which we constructed the annual summary in Table 2, and the fertilizer schedule (Table 3). We did not use grazing numbers of livestock, the DAYCENT model does not use livestock numbers, it assumes a fraction of live and dead dry matter biomass removed". The NWFP attempts to maintain a constant rate of grazing. Using literature from the same study site (Orr et al., 2001, and R. Orr, 2016, pers. comm.), we used fractions of 0.4 (live biomass) and 0.1 (dead biomass)".

3.2.2 The DAYCENT model calibration

The DAYCENT model obtained from the USA had been calibrated for use in that country, so required calibration for a precipitation-heavy UK agriculture. The type of growth module used was changed, from one relating carbon allocation to rainfall, to a module for the UK using a growth based on degree-day accumulation. The climate record for the site, common to all three neighbouring fields, was analysed to determine degree-day parameters

(Supplementary Data, Table S1). The soil parameters were similar, only bulk density and pH were modified for each field (Table 1). Field management for the three grazed fields in the study was unique to each field, for each year (Table 2 and 3).

The calibration was carried out on biomass, followed by soil moisture, soil nutrients, and finally gaseous emission, as advised in the DAYCENT 4.5 INSTRUCTIONS (NREL online, accessed Mar 8, 2019).

There is very little harvest yield data available on the three fields studied. Silage crop fields (for which there is harvest data) surrounding the three used for study and had the same management regime in the same year, the same soil type and climate, and therefore mean field parameters were used to obtain simulated yield. Therefore, the harvest yield of *L. perenne* grass cut for silage was collected from the mean yield data of 10 neighbouring fields to the three study fields, and was compared against the modelled yield for calibration. The DAYCENT model calculates grazed offtake biomass as a proportion of crop yield, so we used this as a proxy for a further check of biomass calibration against measured herbage offtake data from literature. Herbage offtake data from grazing sheep in 1998 was available for the Longlands South field from literature (Orr et al., 2001). The simulated offtake will be variable dependant on the period of livestock grazing and stocking rate, but it should be possible to check the same if the values are in the same vicinity as the literature values for a specific year.

For all other parameters than biomass (soil moisture and runoff, soil N and leached N, and N_2O emission), simulated output using data from the Longlands South field were compared against measured field data to calibrate the model. During the process of calibration using data of Longlands South, parameters were modified and seven calibration versions of the model formed, until the seventh version obtained a balance between the fit of simulated-observed variables for yield, soil water, plant available N and N_2O. Calibrated parameters are listed in S1 of Supplementary Data, all versions of the calibration are listed up to the final calibration reported, to show the complexity and iterative pathway of the calibration process.

Fresh measured field data from fields Dairy North and Golden Rove was used validate the model. No further modifications were made.

Guidance on DAYCENT calibration and validation methods is found in the study by Hartman et al., (2011). Simulated-observed comparison (RMSE, modelling efficiency, coefficient of determination) were carried out on frequent and consistent time-series data, and comparisons against a 1:1 line applied to simulated-observed pairs in cases where missing data interrupted a constant time series. Ratios of areas under the curve (AUC) were also carried out on time series, integrating AUC areas is a statistic commonly used in pharmokinetics, and provides the integral of a plot representing the total amount over time, so that the ratio shows the accumulated relative values (VisualCyp, online accessed 2019; Wu et al., 2012).

After model calibration, it is good practise to do a sensitivity analysis, as model inputs such as soil parameters from field averages contain uncertainty (Wu & Shepherd, 2011; Jørgensen, 1995). A sensitivity analysis was conducted on the DAYCENT model using inputs for the Longlands South field. Changes were made with respect to fertilizer (for a change in soil N), pH, precipitation (for a change in soil moisture) and bulk density; these have previously been the inputs found most likely to influence the N_2O (Fitton et al., 2014b), as a proxy for the effect on general N cycling. Each of the four input parameters was separately modified by an increase and a decrease in 5% and 10% from for the site value, holding the remaining inputs at the field values.

To automate the process, two shell scripts were written in R to run the DAYCENT model in batch mode and collate results, these have been listed in Supplementary Material, S2.

3.3 Climate projections

Previous work with the UK Climate Predictions 2009 (UKCP09) (Wu et al., 2011) has shown that for this study site, climate variation is mild until significant change in the second half of the 21st century. Therefore, we want to determine what effect the climate from latter part of the century will have on traditional pasture management. UKCP09 data for a 30-year period with a mid-point of the 2080s (2070-2099), were used from the UKCP09 website. Two 2080s climate projections were extracted from high and medium GHG emission scenarios corresponding to IPCC A1F1 and A1B scenarios, respectively (IPCC, 2007). The A1F1 scenario is fossil intensive, whereas A1B does not relying too heavily on one particular energy source. Baseline climate was also extracted. The baseline is a stochastic simulation of the North Wyke historic climate (1961-1990), against which climate projection data should be compared. Although created in 2009, and being superceded by UKCP18, a study by the UK Met Office shows that UKCP09 continues to provide a valid assessment of the UK future climate over land and can still be used for adaptation planning (UK Climate Projections, online, accessed December 28, 2018).

The field management for 2011-2015 was continuously repeated each year for the 30-year climate projections. Averages of the climate data and resulting output are reported.

3.4 Calculation of resource use, product and N loss metrics

The f-RUE is an indicator of N use for productivity, whereas the N_2O emission factor (EF) and the emission or leaching per product are indications of the loss of N to the field system.

f-RUE was calculated annually, from grams m^{-2} harvest product / grams m^{-2} nitrogen, from fertiliser applied and livestock excreted (Moll et al., 1982; Sheriff et al., 1982). The harvest product is annual aboveground biomass, or alternatively the live-weight gain of lamb that the biomass would support in these sheep fields. This is based on the average feed conversion of 8 kg dry matter biomass to 1 kg live-weight gain (Eblex sheep BRP manual 5, 2014).

N_2O emission EFs for grassland are calculated annually from simulations using fertilizer and grazing returns of N, and control simulations with zero N applied. EF = g N_2O-N m^{-2} (fertilizer and grazed return to the soil) – g N_2O-N m^{-2} (zero N) / g m^{-2} total N applied. The total N applied is fertilizer N plus N from excreta of grazing animals applied annually (g N m^{-2} y^{-1}) (following Rafique et al, 2011; Barton et al, 2008).

N loss metrics were calculated annually as g N_2O-N m^{-2} (or g N leached m^{-2}) / g harvest product m^{-2}, where harvest product is either g aboveground sward biomass per m^{-2}, or the live-weight gain of lamb that the biomass would support.

DAYCENT outputs most variables in units of g m^{-2} and have been reported as such, as the metrics are ratios of the same units. The exception is EFs which have been reported as kg N_2O-N per kg fertilizer applied (for the same area), for comparison against EFs from literature.

All metrics for the three fields were calculated annually using output from the validated DAYCENT model, for 2011-2015 when precise management records were available, and by 30-year mean for the climate scenarios.

The annual simulations comprising 3 fields, for 5 years (2011-2015) or 30-year climate scenarios, contain managements for grazing only (i.e. no silage harvest) or one silage harvest plus grazing. To test for differences between grazing and silage-grazing managements, a one-sample t-test for one variate with group factor was carried out on each of the metrics produced.

4. Results and Discussion

4.1 Model validation

Measured yield data was very limited. The site is a working farm and documented yield data had been measured when contractors cut grass for silage and weighed grass from a collected harvest from all fields together. So for the calibration of yield, the simulation was based on average field conditions. The simulation of harvest yield is compared against measured yield for 4 harvests (25.05.2011, 09.08.2011, 25.05.2012 and 07.06.2013). The observed dry matter yield of grass grown for silage with means (and standard error) is 6.4 tonnes ha^{-1} (0.20), 5.2 (0.21), 3.8 (0.14) and 6.2 (0.27), corresponding to the afore-mentioned dates. The simulated values (6.15, 4.47, 6.20 and 6.27, respectively) compare favourably against each harvest (RMSE 23.4%, Max error 2.4, despite there only being 4 harvest values to measure). The exception to this was harvests collected on the 25.05.2012. In this case the observed values were unusually low due to physical difficulties in collecting the biomass. This condition existed because of water-logged conditions in the field after heavy and persistent rainfall during the harvest season.

Simulated sheep-grazed herbage offtake per unit area (2011-2014) was also plotted (Fig. 2) against literature values for the same field, Longlands South (Orr et al., 2001). The grazed offtake varies monthly, and varies with the period of livestock grazing and stocking rate, and if there is a silage crop grown before grazing (seen in the 2014 simulated data) whereas the same literature values are repeated from the 1998 season with constant grazing. With fixed values, we cannot properly compare these datasets statistically, because stocking rates will vary and some years will include a silage cut, however as a general guidance they give confidence that simulated grazed offtake values are not unreasonable, and being heavily reliant on simulated biomass, by proxy this serves as an extra check that biomass values are not unreasonable.

Soil N was measured over 4 separate dates and compared to a continuous profile of simulated soil N. Simulated soil NO_3^- and NH_4^+ follow the pattern (Fig. 3a and b, respectively) and value of mean observations quite closely but there is a time lag of about 14 days, the simulations having a more rapid rate of decay than the observations. For both NO_3^- and NH_4^+ there is a large variation in observations for the first date of field measurement, and therefore a large variation in the observed rate of decay between the first and second date of observations.

It is easier to assess the simulated vs. observed soil moisture when using sensors rather than sparse manually sampled data, because sensors provide a continuous profile to match the simulations. Simulation-observation compared favourably overall with no time lag (Fig. 3c). The correlation coefficient between DAYCENT simulated moisture and sensor data was 0.98, modelling efficiency was 0.94 and coefficient of determination was 0.85, which indicated a high positive degree of association. Fig. 3c shows a discrepancy in DAYCENT and sensor soil moisture for the replenishment of soil water after a dry summer. This is because most agricultural models' do not simulate cracking clay soils. On the study fields, the clay soils crack open to create fissures when dry. 2013 was a dry year, while 2012 was not (Fig. 3c). In DAYCENT the 2013 autumn rainfall simulates a rapid increase in soil moisture, but in the cracking clay dry soil a proportion of rainfall bypasses the soil matrix until the cracks have reduced with prolonged rainfall. However most agricultural models do not incorporate a hydrological component for a cracking clay, and overall DAYCENT agrees well overall with sensor values.

DAYCENT matches the occurrence of runoff (0.86 monthly correlation coefficient) but over-estimates it compared to a line connecting the measured values (3.16 AUC ratio, i.e. the ratio between the integrated areas under a daily time-step profile of simulated and measured data), (Fig. 3d). As with soil moisture, this particularly occurs on clay soils when DAYCENT simulates surface runoff after a dry summer with an autumnal increase of precipitation, yet in the field the cracking clays bypass a proportion of the water.

DAYCENT matches the timing of occurrences of observed leached N in soil water runoff (Fig. 3e), although overall the observed values are lower than simulated (0.04 AUC ratio), due to the much higher simulated N leached at fertilizer application. This is likely due to an inherent sensor problem in the way that this type of measuring system misses measurements of leached N, at continuous but low runoff flows which occur frequently at this site. All fertilizer applications were the same, 40 kg N ha^{-1}. Fertilizer is applied when there is a forecast for dry weather to follow application, but forecasts for good weather at this site near the Dartmoor hills often result in a persistent drizzle. This situation occurred in Fig. 3e at the third and seventh fertilizer applications. Persistent drizzle only creates low runoff, under the threshold flow for the N leaching instrument to work. Yet a persistent low runoff immediately after fertiliser application can result in a relatively high daily concentration of N missed by the leaching sensor. Other than this situation, N leaching is reasonably concurrent between simulation and observation.

DAYCENT satisfactorily simulated N_2O emissions for 2013 (Fig.3f) on the Longlands South grass sward (RMSE 102.5; coefficient of determination 0.68; relative error 13.63; mean difference 8.0; n=50, respectively).

Figs. 4a, 4d and 4e show a comparison of simulated-observed variables for the N system over the three swards studied, adding in Dairy North and Golden Rove. Figs. 4b and 4c show a comparison of simulated-observed soil moisture and runoff, reflecting the hydrological processes of the three swards which impact emission and leaching of nitrogen. Field measurements vary spatially whereas a model simulates a field average, so a greater number of outliers can be expected from field observations.

Golden Rove data has, in part, been taken from Horrocks et al. (2014), but over the same growing season as the other two fields. Golden Rove has a more variable slope across the field, which explains the greater variability in observed soil water runoff compared to other fields.

For most simulated-observed pairs in Fig. 4, the dense area of points on the plots falls near the 1:1 line. Soil inorganic N simulation generally appears to be lower than observed data (Fig. 4a), but Fig. 3a and b suggest the cause is a faster rate of soil N assimilation in the DAYCENT model than measured, however measured soil inorganic N data is in limited supply and also variable.

For the North Wyke site with high rainfall and heavy clays, the N_2O emissions have been described as higher than most sites (Fitton et al., 2014a). If we alter DAYCENT calibration parameters relating to nitrification and denitrification to match a high measured rate of gaseous emission, we also speed up the depletion of soil inorganic N. Smaller estimation of soil N by DAYCENT compared to measurement is known and has been described in literature (Senapati et al., 2016).

Over several fields the occurrence of daily simulated and observed leached N is concurrent, generally simulations are higher than observations but data has a wide spread. Since daily values are so variable, leached data is accumulated annually for use in the metrics. Annual simulations-observations compare better than daily, by a simulated to measured ratio of 1.5:1, however the under-estimation inherent in this type of sensor system for leached inorganic N has been discussed earlier.

The simulated-observed daily N_2O emissions are spread widely and evenly over the plot (Fig.4e), and field measurements have provided outliers, but individual field profiles have shown reasonable agreement with observations (Dairy North 2015 and Golden Rove 2012: RMSE 157.5, 148.1, n=105, 18; respectively). N_2O will be accumulated annually for the metrics and EFs to even out differences in response rate to emission stimuli (as per Senapati et al., 2016 who found discrepancies between measured and simulated daily N_2O fluxes, but good agreement on annual accumulations).

Summarizing, it was always going to be difficult to attempt a multi-parameter system calibration of a model, rather than focussing on a desired parameter, because modifications made on one component of the model will inevitably lead to changes in other areas, nevertheless this is what we have attempted. DAYCENT simulated soil N and daily N leached with a sizeable uncertainty, however replicate soil sampling showed a high variation and was limited in temporal occurrence, and observed leached N data is temporal by nature without replicates to show spatial variability of leaching. Despite a farm platform that aiming to provide data for modelling, it can never be a perfect set-up or frequency of sampling for all models. DAYCENT simulated dry matter biomass, soil moisture, N_2O and monthly leached N with a reasonable degree of agreement. Previous studies have shown that DAYCENT does under-estimate N_2O (Wang et al., 2017), also that North Wyke soil produces high N_2O emissions (in Fitton et al., 2014a, whose study on N_2O emissions focused on the Rowden fields nearby with the same soil type). The variables related to N in the system indicate that to obtain a reasonable simulation of N_2O, the calibration may inadvertently increase the rate of N turnover in the soil, shown by a faster rate of simulated soil NH_4^+ and NO_3^- decrease, although the uncertainty in soil observations is high because of the low sampling frequency. Senapati et al. (2016) have similarly commented on this relationship of soil N transformations and N_2O emission.

Fig.5 displays a spider plot as the result of a sensitivity analysis with respect to N_2O emission. Sensitivity was expressed as percentage change in the simulated variable compared to its original base simulation (Senapati et al., 2016). For a change of +/- 10% and 20%, the bulk density, fertilizer and precipitation were found to be influential, in agreement with the literature (Fitton et al., 2014b). Modified precipitation (being an indirect way for modifying soil moisture) is the only factor to increase the total N_2O in the drying and wetting of soils, i.e. via nitrification and denitrification. Fertilizer increase results in an exponential increase in nitrous oxide, and increased bulk density produces general increase in N_2O. Modifying only pH did not have a conclusive effect on N_2O emissions in the model simulations we used. The process leading to nitrogen emission does not proceed linearly, but in multiple stages of which the last stage is the loss of N to the atmosphere (Butterbach-Bahl et al., 2013), which means it is more likely for factors to have an effect in unison whereas a sensitivity analysis isolates the effect of each factor".

Our sensitivity analysis likely explains differences in simulated output between Golden Rove and the other two fields, with Golden Rove having the lowest bulk density of 0.9 for the top 10cm depth of its clay loam compared to 1.07. Although all soils are of the Halstow series, bulk density will vary with soil compaction and soil organic matter content, which are related to previous field management. Comparatively, Senapati et al. (2016) found DAYCENT to be most sensitive to field capacity and a decrease in bulk density, followed by pH, fertilizer-N and soil organic matter.

4.2 Metrics from validated model simulation (accumulated annually)

4.2.1 Resource use efficiency

Table 4 shows f-RUE, the annual aboveground biomass per unit N applied (both from fertilizer and stock returns) simulated by DAYCENT for each of the three fields. This is shown to be variable, both between years 2011-15 and between the three fields. Dairy North has the highest f-RUE and Longlands South the lowest.

It is unclear from f-RUE whether higher or lower values result from biomass or fertilizer variation. In fact, the higher f-RUE value of 115.4 in 2014 for Dairy North hides the information that only 80 kg fertilizer N ha^{-1} was applied (150 kg N ha^{-1} is the 5-year average), a reduction in N applied did not reduce the aboveground biomass by the same proportion, hence increasing the f-RUE value. Eliminating the high f-RUE value for 2014, gives very similar resource efficiency levels for the three fields, with Golden Rove as the largest.

4.2.2 N_2O Emission Factor

The 2011-2015 average annual simulated N_2O (minus zero N emission) for Longlands South, Dairy North and Golden Rove were 6.9, 7.9 and 5.9 kg N_2O-N ha^{-1}, respectively. If the Tier 1 IPCC EFs are applied, based on the fertilizer applied and grazing returns, they estimate respective emissions of 2.3, 2.1 and 2.0 kg N_2O-N ha^{-1}. If Tier 1 EFs were added for the crop residue from the amount of standing dead leaf litter, respective emission estimates would be 2.6, 2.5 and 2.2 kg N_2O-N ha^{-1}.

The 2011-2015 average annual EFs obtained in this study for Longlands South, Dairy North and Golden Rove were 0.031, 0.041 and 0.029 kg N_2O-N per kg fertilizer N applied, respectively (Table 5), compared with the IPCC Tier 1 EFs of 0.01.

Our model compares satisfactorily with the literature. For Irish grassland, Rafique et al. (2011) calculated EFs at 0.01 – 0.031 and Hyde et al. (2006) at 0.007 – 0.05. For Scottish grasslands Dobbie and Smith (2003) reported EFs at 0.01 – 0.03. Cardenas et al. (2010) reported a N_2O flux minus background flux of 3.9 kg N_2O–N ha^{-1} yr^{-1}, for the west of England in a field close to this study, using a fertilizer application of 100 kg N ha^{-1}, resulting in an EF of 0.039.

All these studies have a higher limit than the 2006 IPCC EF of 0.01 for direct N_2O emissions. Deviations of observed N_2O emissions from those calculated using the IPCC Tier 1 EF approach clearly shows that this methodology is too simplistic to reflect regional variations of biologically produced N_2O emissions (Skiba et al., 2012). The Department for Environment, Food and Rural Affairs and devolved UK governments funded the GHG Platform in order to improve the UK's agricultural greenhouse gas emission inventories which should improve regional N_2O EFs. Research since the adoption of the IPCC EF for grassland strongly suggests that weather and management modifies EFs. Smith et al. (1999) cite UK studies with EF maxima of 1.4 to 7.1 kg N_2O-N per kg fertilizer N applied.

It is only possible to compare N_2O simulation for the 5 years of available management data in the early 21st century against the 30-year mean for the climate projections in the late 21st century. We recognize that the weather of 2011-2015 will not encompass the extremes encountered in 30 years.

The climate projection for the latter part of the 21st century, at medium and high GHG levels, has been applied to N_2O simulation, plus its stochastic baseline. The earliest observed 30-year mean climate record available for North Wyke (1982-2011) has a mean temperature of 10.0 degrees C and 1043.3 mm precipitation, so the baseline stochastic temperature (Table 5b) is slightly lower than the 30-year record and also the mean of 2011-15 (Table 5a), and the baseline stochastic precipitation falls between the 30-year mean and the mean of 2011-15.

Baseline climate N_2O EFs are higher than 2011-2015, partly because the differences in a 30-year period to a 5-year period. This is also partly because we cannot re-create the same concurrence between baseline stochastic precipitation / temperature and the time of fertilizer application date or grazing period in the same way as it occurred 2011 – 2015.

For UK climate projections, the baseline climate produces EFs of 0.056, 0.076 and 0.048 kg N_2O-N per kg applied fertilizer for Longlands South, Dairy North and Golden Rove, respectively. The medium GHG emission climate projection (36.6% increase of mean temperature over baseline climate) increased EFs by a value of 0.03, 0.01 and 0.03 respectively, above baseline climate. The high GHG emission climate projection (48.4% increase of mean temperature) increased EFs by a value of 0.03, 0.03 and 0.03, respectively.

Simulated N_2O EFs for Golden Rove are lower than the other fields, the sole exception being 2011. This is due to the lower top-soil bulk density, which is considered a key factor in reducing emission via the soil porosity and hence oxygen levels reducing microbial denitrification (Oenema et al., 1997). However, a factor to also bear in mind is the DAYCENT model's known sensitivity to bulk density.

The aim of a calibrated model is to obtain a reasonable agreement for the fit of all simulated output against measured data, and to do this generically for a crop and soil type, therefore we do not expect to obtain a perfect fit for all variables for all fields. A source of error in measured data is the spatial heterogeneity of the physical and biological factors in a grazed field that control the rate of N_2O emissions. The limited area of static chambers covering the field means that it is possible that N_2O emissions are under- or over-estimated (Chadwick et al., 2014). This is especially true for N hotspots created by urine patches (Cowan et al., 2015), and it is difficult when setting up static chambers to know beforehand where these exist. The chambers are moved every few weeks to a different part of a field containing livestock, this results in hotspots from fresh urine being covered and therefore varying values of soil N as the chambers are moved around the field, whereas a model simulates the processes of nutrient cycling resulting from the average rate of N applied to the field.

4.2.3 N_2O or leaching per unit product

Averaged over 2011 - 2015, 0.002 g N_2O-N m^{-2} was emitted annually per g m^{-2} of aboveground sward biomass (Table 6a) for all three fields, and 0.016 g N_2O-N m^{-2} was emitted annually per g m^{-2} of grazing stock live-weight gain. N_2O per product is shown to be consistent, both between fields and between years 2011 - 2015. There appears little increase in these metrics under future climate projections (Table 6b) from the baseline values; but this metric hides the fact that with warmer projected temperatures there is a corresponding increase in biomass plus a proportional increase in annual N_2O emissions.

In contrast to N_2O, the inorganic N leached per unit product 2011-2015 was variable (Table 7a), both between years and between fields, averaging from 0.0025 – 0.004 g N m^{-2} leached per g m^{-2} aboveground sward biomass, and averaging from 0.016 – 0.032 g N m^{-2} leached per g m^{-2} of grazing stock live-weight gain. These metrics represent 27 kg to 45 kg leached N ha^{-1} annually. The average annual fertilizer applied over 2011 - 2015 was 16.3, 14.4 and 17.2 kg N ha^{-1} for Longlands South, Dairy North and Golden Rove, respectively. Total days grazing over 2011-2015 were 919, 764 and 614 days for Longlands South, Dairy North and Golden Rove. Because fertilizer N inputs for the three fields were similar, the reason behind higher leaching of Longlands South is likely animal derived, the longer the total period of grazing over a year, the higher the risk of leaching (Cuttle et al., 1998).

The climate projection under both the medium and high GHG scenarios (Table 7b) resulted in a small increase in leaching above the baseline scenario together with a small increase in biomass, resulting in a small increase in inorganic N leached per unit product.

Based on the same simulated units of g m^{-2}, metrics for leaching per unit product are smaller than N_2O emissions per unit product. This agrees with other findings from DAYCENT which showed that fine textured soils emit more N_2O, but with smaller leaching losses (Del Grosso et al., 2008).

In this study the Dairy North field with the highest f-RUE was also the field with the lowest leached N per unit product, and Longlands South field with the lowest f-RUE was also the field with the highest leaching. Norton et al. (2015) reported that improvements in N use efficiency from increased productivity coincide with reductions in N pollution of surface waters.

4.2.4 Significant differences between managements for grazing or silage crop with grazing

The annual simulations contain a mixture of field management types, either grazing only or one silage harvest plus grazing. There was a significant difference ($p<0.05$) in the simulated N_2O emission per unit product, with values for the grazing only management found to be significantly higher than the silage plus grazing management. This disproves the null hypothesis that the two managements would result in the same yield gain to N loss. The higher N_2O emission per unit product for grazing only management related to the total period livestock spent on pasture, which were 171 – 277 days per year for grazing only, and 27 – 152 days per year for silage plus grazing. Total annual inorganic fertilizer applied was not significantly different between the two managements. N_2O emission in grazed pastures are known to be primarily associated with animal excreta and soil compaction from livestock (Saggar et al., 2004; 2007) rather than resulting indirectly from a reduction in the grass biomass (Zhang et al., 2015), and livestock numbers plus number of grazing days have shown an increase in N_2O (Wang et al., 2012). Here however, the simulated grazing intensity is assumed constant, and the DAYCENT model does not directly simulate grazing intensity with livestock numbers. The metrics for leaching, fertilizer N use efficiency or EFs did not display a significant difference between the silage plus grazing management and the grazing management.

5. Conclusion

By applying the automated sensor data to model calibration, the simulations provided continuous data to create the metrics to build up a picture for the health of the field system in terms of gains in product offset by the losses in nitrogen.

Comparing the three field systems, there appeared to be no difference in absolute leached N, but Golden Rove was better in terms of efficiency with lower average leached N per unit product (0.0032 for Golden Rove, compared to 0.004 and 0.003 (ignoring 2012)), and had the highest resource use efficiency (48.2 biomass : applied N, compared to 46.5 and 45.2). N_2O emission was lower on Golden Rove (0.029 kg N_2O-N per kg fertilizer applied, compared to 0.041 and 0.031) which is due to lower topsoil bulk density, enhanced by the model's sensitivity to bulk density.

Warmer temperature projections for the latter 21st century increased N_2O EFs consistently across all fields under medium and high GHG scenarios compared to baseline (from baseline 0.045, 0.056 and 0.075 kg N_2O-N per kg fertilizer applied, to 0.048, 0.059 and 0.077). Although Golden Rove had the lowest N_2O EF, using one metric does not show the whole picture, because the leached N per product was relatively high amongst the three fields (0.0033 for Golden Rove, compared to 0.0040 and 0.0041).

Separating results for N_2O emission per product into different field managements of silage harvest followed by grazing versus grazing only, added a further dimension to the picture showing that reduced days grazing annually was coincident with reduced emission (0.001 N_2O-N : biomass, compared to 0.0018, respectively), disproving the hypothesis that all management yields the same gain to loss.

If we simulate both N loss by leaching and by gaseous emission, we get a fuller picture of the loss, and comparison to product gained adds information on efficiency, separation into field management categories adds further data. By using several metrics and layering up more information, field sites or management techniques are better compared than relying on one metric. This study has produced metrics for traditional management of sheep ryegrass pasture. New technology for field management, new cultivars or livestock breeds for greater yield can have unintended consequences of the loss of nitrogen to air or water. If in future, metrics for agronomic innovations are compared to those for traditional management under current climate and future climate projections, we will be able to determine the relative benefits and offsets.

Acknowledgement

This study was partially supported by Soil to Nutrition, Rothamsted Research’s Institute Strategic Programme supported by the Biotechnology and Biological Sciences Research

Council (BBS/E/C/000I0320). The North Wyke Farm Platform is a UK National Capability, also supported by the Biotechnology and Biological Sciences Research Council (BBS/E/C/000J0100). This study was also partially supported by the Natural Environment Research Council’s ADVENT project (NERC NE/M019691/1). Climate data were measured at the MIDAS Land Surface Station DLY3208 DEVON, UK, a weather station of the UK Meteorological Office. We would especially like to thank Dr Nadine Loick of Rothamsted Research for advice on preparation of N_2O model calibration parameters, and the data team of the North Wyke Farm Platform. We owe our gratitude to the late Mr Robert Orr, grassland specialist at the North Wyke site, for his invaluable advice and information on sward growth.

Supplementary data

Supplementary data: S1. DAYCENT calibration parameters.

Supplementary data: S2. Two example R scripts to batch process DAYCENT, and batch extraction of output

References

Abbasi, M.K., Adams, W.A., 1998. Loss of nitrogen in compacted grassland soil by simultaneous nitrification and denitrification. Plant Soil, 200, 265–277. doi: 10.1023/A:1004398520150.

Agriculture and Horticulture Development Board (AHDB) Beef and Lamb manual, 2016. Planning grazing strategies for better returns. http://beefandlamb.ahdb.org.uk/wp/wp-content/uploads/2016/07/BRP-Planning-grazing-strategies-manual-8-150716.pdf, (accessed Feb 15, 2019).

ASA Analytics, Nitrogen in wastewater. http://www.asaanalytics.com/total-nitrogen.php, (accessed Dec. 28, 2018).

Barton, L., Kiese, R., Gatter, D., 2008. Nitrous oxide emissions from a cropped soil in a semi-arid climate. Glob. Change Biol., 14, 177–92. doi: 10.1111/j.1365-2486.2007.01474.x.

Butterbach-Bahl K., Baggs E.M., Dannenmann M., Kiese R., Zechmeister-Boltenstern S. 2013. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci., 368, 20130122.

Cardenas, L.M., Hawkins, J.M.B., Chadwick, D., Scholefield, D., 2003. Biogenic gas emissions from soils measured using a new automated laboratory incubation system. Soil Biol. Biochem., 35, 867–870. doi: 10.1016/S0038-0717(03)00092-0.

Cardenas, L.M., Thorman, R., Ashlee, N., Butler, M., Chadwick, D., Chambers, B., Cuttle, S., Donovan, N., Kingston, H., Lane, S., Dhanoa, M.S., Scholefield, D. 2010. Quantifying annual N_2O emission fluxes from grazed grassland under a range of inorganic fertiliser nitrogen inputs. Agr., Ecosys. Environ., 136, (3-4) 218–226. doi: 10.1016/j.agee.2009.12.006.

Chadwick, D.R., Cardenas, L., Misselbrook, T.H., Smith, K.A., Rees, R.M., Watson, C.J., McGeough, K.L., Williams, J.R., Cloy, J.M., Thorman, R.E., Dhanoa, M.S., 2014.

Optimizing chamber methods for measuring nitrous oxide emissions from plot based agricultural experiments. Eur. J. Soil Sci., 65, 295–307. doi: 10.1111/ejss.12117.

Cowan, N., Norman, P., Famulari, D., Levy, P.E., Reay, D.S., Skiba, U., 2015. Spatial variability and hotspots of soil N_2O fluxes from intensively grazed grassland. Biogeosciences, 12, 1585 – 423 1596. doi: 10.5194/bg-12-1585-2015.

Crutzen, P.J. 1970. The influence of nitrogen oxide on the atmospheric ozone content. Quarterly Journal of the Royal Meteorological Society, 96320, 325.

Cuttle, S.P., Scurlock, R.V., Davies, B.M.S., 1998. A 6-year comparison of nitrate leaching from grass/ clover and N-fertilized grass pastures grazed by sheep. J. Agr. Sci., 131, 39-50. doi: 10.1017/S0021859698005565.

Defra. Fertiliser manual (RB209). 2010. Norwich: TSO.

Del Grosso, S. J., Parton, W.J., Mosier, A.R., Walsh, M.K., Ojima, D.S., Thornton, P.E., 2006. DAYCENT National-Scale Simulations of Nitrous Oxide Emissions from Cropped Soils in the United States. J. Environ. Qual., 35 (4), 1451-1460. doi:10.2134/jeq2005.0160.

Del Grosso, S. J., Parton, W. J., Ojima, D. S., Keough, C. A., Riley, T. H., and Mosier, A. R., 2008. DAYCENT Simulated Effects of Land Use and Climate on County Level N Loss Vectors in the USA, in: Hatfield, J.L., Follett, R.F. (Eds.), Nitrogen in the Environment: Sources, Problems, and Management. Second edition. Academic Press/Elsevier, Amsterdam, Boston.

Diaz, R.J. and Rosenberg, R. 2008. Spreading Dead Zones and Consequences for Marine Ecosystems. Science, 926-929. doi: 10.1126/science.1156401.

Dobbie, K.E., Smith, K.A., 2003. Nitrous oxide emission factors for agricultural soils in Great Britain: the impact of soil water-filled pore space and other controlling variables. Glob. Change Biol., 9, 204–18. doi: 10.1046/j.1365-2486.2003.00563.x.

Eblex, 2014. Sheep BRP manual 5. http://beefandlamb.ahdb.org.uk/wp/wp-content/uploads/2014/07/brp-manual-5-Growing-and-finishing-lambs290714.pdf, (accessed Feb. 20, 2019).

Eblex, 2016. Beef and sheep BRP manual 8. http://beefandlamb.ahdb.org.uk/wp/wp-content/uploads/2016/07/BRP-Planning-grazing-strategies-manual-8-150716.pdf, (accessed Feb. 20, 2019).

US Environmental Protection Agency Science Advisory Board. 2011. Reactive Nitrogen in the United States: An Analysis of Inputs, Flows, Consequences and Management Options. EPA Report: EPA-SAB-11-013.

Field, P., Ball, R., Theobald, P.W., 1985. Leaching of nitrate from sheep-grazed pastures. Pr. N. Z. Grassl. Assoc., 46, 209-214.

Fitton, N., Datta, A., Hastings, A., Kuhnert, M., Topp, C.F.E., Cloy, J.M., Rees, R.M., Cardenas, L.M., Williams, J.R., Smith, K., Chadwick, D. and Smith, P., 2014a. The challenge of modelling nitrogen management at the field scale: simulation and sensitivity analysis of N_2O fluxes across nine experimental sites using DailyDayCent. Environ. Res. Lett., 9, 095003, 15pp. doi:10.1088/1748-9326/9/9/095003.

Fitton, N., Datta, A., Smith, K., Williams, J.R., Hastings, A., Kuhnert, M., Topp, C.F.E., Smith, P., 2014b. Assessing the sensitivity of modelled estimates of N_2O emissions and yield to input uncertainty at a UK cropland experimental site using the DailyDayCent model. Nutr. Cycl. Agroecosys., 99, 119–133. doi: 10.1007/s10705-014-9622-0.

Hartman, M.D., Merchant, E.R., Parton, W.J., Gutmann, M.P., Lutz, S.M., Williams, S.A., 2011. Impact of historical land-use changes on greenhouse gas exchange in the U.S. Great Plains, 1883-2003. Ecol. Appl., 21 (4), 1105–1119. doi: 10.1890/10-0036.1.

Hayati, D., Ranjbar, Z., Kamari, E., 2010. Measuring Agricultural Sustainability, in: Lichtfouse, E. (Ed.), Biodiversity, Biofuels, Agroforestry and Conservation Agriculture, Sustainable Agriculture Reviews 5. Springer Science + Business Media B.V. doi: 10.1007/978-90-481-9513-8_2.

Heinemann, J.A., Massaro, M., Coray, D.S., Agapito-Tenfen, S.Z., Wen, J.D., 2013. Sustainability and innovation in staple crop production in the US Midwest. Int. J. Agric. Sustain., 12, 71-88. doi: 10.1080/14735903.2013.806408.

Henderson, B.B., Gerber, P.J., Hilinski, T.E., Falcucci, A., Ojima, D.S., Salvatore, M., Conant, R.T. 2015. Greenhouse gas mitigation potential of the world's grazing lands:

Modeling soil carbon and nitrogen fluxes of mitigation practices. Agriculture, Ecosystems & Environment, 207, 91-100.

Horrocks, C.A., Dungait, J.A.J., Heal, K.V., Cardenas, L.M., 2014. Comparing N_2O fluxes from recently created extensive grasslands and sites remaining under intensive agricultural management. Agriculture, Ecosystems and Environment 199 (2014) 77–84. doi: 10.1016/j.agee.2014.08.018.

Hyde, B.P., Hawkins, M.J., Fanning, A.F., Noonan, D., Ryan, M., Toole, P.O., Carton, O.T., 2006. Nitrous oxide emissions from a fertilized and grazed grassland in South East of Ireland. Nutr. Cycl. Agroecosys., 75, 187–200. doi: 10.1007/s10705-007-9099-1.

IPCC. 2007. Summary for Policymakers, in: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jørgensen, S.E., 1995. State of the art of ecological modelling in limnology. Ecol. Model., 78, 101–115. doi: 10.1016/0304-3800(94)00120-7.

Lehmann, J., Schroth, G., 2003. Nutrient leaching, in: Schroth, G., Sinclair, F.L. (eds.) Trees, Crops and Soil fertility - Concepts and Research methods. CAB International, Wallingford, UK. 16pp.

Loick, N., Dixon, E.R., Abalos, D., Vallejo, A., Matthews, G.P., McGeough, K.L., Well, R., Watson, C.J., Laughlin, R.J., Cardenas, L.M., 2016. Denitrification as a source of nitric oxide emissions from incubated soil cores from a UK grassland soil. Soil Biol. Biochem., 95, 1-7. doi: 10.1016/j.soilbio.2015.12.009

Mekala, C., Nambi, I.M., 2016. Transport of ammonium and nitrate in saturated porous media incorporating physiobiotransformations and bioclogging. Bioremediat. J., Volume 20 (2), 117-132, doi: 10.1080/10889868.2015.1113925.

Metherell, A.K., Harding, L.A., Cole C.V., Parton, W.J., 1993. CENTURY Soil Organic Matter Model Environment, Technical Documentation, Agroecosystem Version 4.0, Great Plains System Research Unit, Technical Report No. 4, USDA-ARS, Fort Collins, Colorado. http://www.nrel.colostate.edu/projects/century/century-documentation.php, (accessed Mar. 1, 2019).

McCloud, D.E., Bula, R.J., Shaw, R.H., 1964. Plant Field Physiology. III. Environmental Elements. B. Temperature. Adv. Agron., 16, l-58. doi: 10.1016/S0065-2113(08)60020-6.

Moll, R.H., Kamprath, E.J., Jackson W.A. 1982. Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. Agron. J., 74, 562–564. doi: 10.2134/agronj1982.00021962007400030037x.

Norton, R., Davidson, E., Roberts, T. 2015., Nitrogen Use Efficiency and Nutrient Performance Indicators. Technical Paper 01/2015. Global Partnership on Nutrient Management Task Team Workshop, December 8, 2014 held at Washington, DC.

NREL, DAYCENT 4.5 INSTRUCTIONS - General instructions for DayCent 4.5. including documentation on DayCent specific input and output files. NREL model source http://www.nrel.colostate.edu/assets/nrel_files/projects/daycent/downloads/DayCent4.5.Instructions.txt, (accessed Mar 8, 2019).

Oenema, O., Velthof, G.L., Yarnulki, S., Jarvis, S.C., 1997. Nitrous oxide emissions from grazed grassland. Soil Use Manage., 13, 288-295. doi: 10.1111/j.1475-2743.1997.tb00600.x.

Orr, R.J., Martyn, T.M., Clements, R.O., 2001. Evaluation of perennial ryegrass varieties under frequent cutting or continuous stocking with sheep. Plant Var. Seeds, 14, 181-199

Orr, R. J., Murray, P. J., Eyles, C. J., Blackwell, M.S.A., Cardenas, L.M., Collins, A.L., et al., 2016. The North Wyke Farm Platform: effect of temperate grassland farming systems on soil moisture contents, runoff and associated water quality dynamics. Eur. J. Soil Sci., 67, 374–385. doi: 10.1111/ejss.12350.

Parton, W.J., Hartman, M.D., Ojima, D.S., Schimel, D.S., 1998. DAYCENT: Its land surface sub-model: description and testing. Global Planet. Change, 19, 35-48. doi: 10.1016/S0921-8181(98)00040-X.

Parton, W.J., Ojima, D., Del Grosso, S., Keough, C., Century Tutorial, Supplement to CENTURY Users manual. http://www.nrel.colostate.edu/projects/century/century-workbook.php, (accessed Feb 5, 2019).

Pineiro, G., Paruelo, J.M., Jobbagy, E.G., Jackson, R.B., Oesterheld, M., 2009. Grazing effects on belowground C and N stocks along a network of cattle exclosures in temperate and subtropical grasslands of South America. Global Biogeochem.Cy., 23, GB2003. doi: 10.1029/2007GB003168.

Rafique, R., Hennessy, D., Kiely, G., 2011. Nitrous oxide emission from grazed grassland under different management systems. Ecosystems, 14(4), 563–582. doi: 10.1007/s10021-011-9434-x.

Rafique, R., Kumar, S., Luo, Y., Kiely, G., Asrar, G., 2015. An algorithmic calibration approach to identify globally optimal parameters for constraining the DayCent model. Ecol. Model., 297, 196–200. doi 10.1016/j.ecolmodel.2014.11.022.

Saggar, S., Bolan, N.S., Bhandral, R., Hedley, C.B., Luo, J., 2004. A review of emissions of methane, ammonia and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. New Zeal. J. Agr. Res., 47, 513–544. doi: 10.1080/00288233.2004.9513618.

Saggar, S., Hedley, C.B., Giltrap, D.L., Lambie, S.J., 2007. Measured and modelled estimates of nitrous oxide emission and methane consumption from sheep-grazed pasture. Agr., Ecosys. Environ., 122, 357–362. doi: 10.1016/j.agee.2007.02.006.

Senapati, N., Chabbi, A., Giostri, A.F., Yeluripati, J.B., Smith, P., 2016. Modelling nitrous oxide emissions from mown-grass and grain-cropping systems: Testing and sensitivity analysis of DailyDayCent using high frequency measurements. Sci. Total Environ., 572 (1), 955–977. doi: 10.1016/j.scitotenv.2016.07.226.

Sheriff, D.W., Margolis, H.A., Kaufmann, M.R., Reich, P.B., 1995. Resource use efficiency, in: Smith, W.K., Hickley, T.M. (Eds.), Resource physiology of conifers. Academic Press, San Diego, CA.

Siemens, J., Kaupenjohann, M., 2002. Contribution of dissolved organic nitrogen to N leaching from four German agricultural soils. J. Plant Nutr. Soil Sci., 165 (6), 675–681. doi: 10.1002/jpln.200290002.

Skiba, U., Jones, S.K., Dragosits, U., Drewer, J., Fowler, D., Rees, M., Pappa, V.A., Cardenas, L., Chadwick, D., Yamulki, S., Manning, A.J., 2012. UK emissions of the greenhouse gas nitrous oxide. Philos. T. Roy. Soc. B., 367 (1593), 1175–1185. doi: 10.1098/rstb.2011.0356.

Smith, K.A., Bouwman, L., and Braatz, B. ,1999. Nitrous oxide: Direct emissions from agricultural soils. Background paper for IPCC Workshop on Good Practice in Inventory Preparation: Agricultural Sources of Methane and Nitrous Oxide, 24-26 February 1999, Wageningen, The Netherlands.

Tilman’ D., Cassman’ K.G., Pamela A. Matson, P.A., Rosamond Naylor’ R., Polasky’ S., 2002. Agricultural sustainability and intensive production practices. Nature, 418, 671-677. doi: 10.1038/nature01014.

UK Climate Projections, http://ukclimateprojections-ukcp09.metoffice.gov.uk/24127, (accessed December 28, 2018).

VisualCyp, Interactions Explorer software online, https://sites.google.com/site/visualcypnet/our-company/auc-ratio, accessed Mar 8, 2019.

Wang, J., Cardenas, L.M., Misselbrook, T.M., Cuttle, S., Thorman, R.E., Li, C., 2012. Modelling nitrous oxide emissions from grazed grassland systems. Environ. Pollut., 162, 223-233. doi:10.1016/j.envpol.2011.11.027.

Wang, Y., Dou, F., Storlien, J.O., Wight, J.P., Paustian, K.H., Del Grosso, S.J., and Hons, F.M., 2017. Simulating Impacts of Bioenergy Sorghum Residue Return on Soil Organic Carbon and Greenhouse Gas Emissions Using the DAYCENT Model, in: Field, D., Morgan, C.L., McBratney, A.B. (Eds.), Global Soil Security, Progress in Soil Science. Springer International Publishing, Switzerland. doi: 10.1007/978-3-319-43394-3_15.

K Wu, EEW Cohen, LK House, J Ramírez, W Zhang, MJ Ratain, and RR Bies. 2012. Nonlinear Population Pharmacokinetics of Sirolimus in Patients With Advanced Cancer. CPT: Pharmacometrics & Systems Pharmacology 1(17). doi:10.1038/psp.2012.18.

Wu, L., Shepherd, A., 2011. Special Features of the SPACSYS Modeling Package and Procedures for Parameterization and Validation, in: Laj R. Ahuja, L.R., Ma, L. (Eds.), Advances in Agricultural Systems Modeling. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America doi: 10.2134/advagricsystmodel2.c4.

Zhang, L., Hou, L., Laanbroek, H.J., Guo, D., Wang, Q., 2015. Effects of Mowing Heights on N_2O Emission from Temperate Grasslands in Inner Mongolia, Northern China. Amer. J. Clim. Change, 4, 397-407. doi: 10.4236/ajcc.2015.45032.

Fig.1. The North Wyke Farm Platform, fields in study outlined.

Fig.2. Monthly grazed biomass offtake on Longlands South, simulated values against fixed 1998 monthly values from literature on the same field.

Fig.3. Longlands South field simulated-observed time series plots for soil (a) nitrate (b) ammonium (c) moisture (d) runoff (e) leached inorganic nitrogen (f) nitrous oxide emission.

Fig.4. Three-field simulated-observed plots for soil (a) total inorganic nitrogen (b) moisture (c) runoff (d) leached inorganic nitrogen (e) nitrous oxide emission, on the fields of Longlands South (LS), Dairy North (DN), and Golden Rove (GR).

Fig.5. Sensitivity Analysis of DayCent focussing on Nitrous Oxide.

Table 1. Soil parameters, LS=Longlands South, DN=Dairy North, GR=Golden Rove

Soil parameters	LS	DN	GR
Field area (ha)	1.75	1.78	3.85
Soil type	Halstow soil series	Halstow soil series	Halstow Soil series
Bulk Density ($g\ cm^{-3}$) (0-30 cm)	1.07	1.07	0.9 (0-10 cm)/ 1.05 (11-30 cm)
Field Capacity (volumetric %) (avg 0-30 cm)	36.5	37.3	37.3
Permanent Wilting Point (volumetric %) (avg 0-30 cm)	17.5	17.5	17.5
pH (0-10 cm)	5.48	5.78	5.72

Table 2. Field management 2011-2015. No. of days grazed, commercial fertilizers and farm yard manure (FYM) applied. LS=Longlands South, DN=Dairy North, GR=Golden Rove; inorganic fertilizer application area is 1.69, 1.74 and 3.78 ha, respectively; FYM (0.12% N) organic application area is 3.28ha on GR.

Field, Year & Fertilizer type	Application (App) (kg)	App Rate of N (kg ha^{-1})	Harvest & Grazing
LS 2011 Nitram	982	App*0.345/Area = 200	180 days grazed
LS 2012 Nitram	393	80	277 days grazed
LS 2013 Nitram	736	150	171 days grazed
LS 2014 Nitram	657	134	June harvest; 139 days grazed
LS 2014 20-8-12-7	726	App*0.2/Area = 86	
LS 2015 Nitram	812	166	Aug harvest; 152 days grazed
DN 2011 Nitram	1007	200	180 days grazed
DN 2012 Nitram	403	80	186 days grazed
DN 2013 Nitram	799	158	196 days grazed
DN 2014 Nitram	409	81	June harvest; 27 days grazed
DN 2015 Nitram	1002	199	175 days grazed
GR 2011 Nitram	1753	160	179 days grazed
GR 2011 25-0-13	756	50	
GR2012 Nitram	438	40	May & Aug harvest; 49 days grazed
GR 2012 20-8-12-7	1512	80	
GR2013 Nitram	709	65	June harvest; 130 days grazed
GR 2013 22-4-14-7	1496	App*0.22/Area = 87	
GR 2014 Nitram	1747	159	210 days grazed
GR 2015 Nitram	1352	123	Sept harvest; 46 days grazed
GR 2015 25-0-13-7	1182	App*0.25/Area = 78	

Table 3. Fertilizer Schedule: Application Dates (and application rate, kg N/ha)
G = grazed only, HG = one harvest and grazed, 2HG = two harvests and minimal grazing

Longlands South	2011	G	07/03/2011 (40)	11/04/2011 (40)	05/05/2011 (40)	06/06/2011 (40)	05/07/2011 (40)
	2012	G	22/05/2012 (40)	19/06/2012 (40)			
	2013	G	05/03/2013 (40)	10/04/2013 (40)	07/05/2013 (40)	06/06/2013 (30)	
	2014	HG	19/04/2014 (86)	02/05/2014 (40)	25/06/2014 (50)	21/07/2014 (44)	
	2015	HG	19/03/2015 (40)	28/04/2015 (44)	26/05/2015 (42)	22/06/2015 (40)	
Dairy North	2011	G	04/03/2011 (40)	11/04/2011 (40)	05/05/2011 (40)	06/06/2011 (40)	05/07/2011 (40)
	2012	G	22/05/2012 (40)	19/06/2012 (40)			
	2013	G	05/03/2013 (39)	10/04/2013 (39)	07/05/2013 (39)	06/06/2013 (41)	
	2014	HG	28/04/2014 (40)	08/07/2014 (41)			
	2015	G	19/03/2015 (36)	28/04/2015 (41)	26/05/2015 (41)	22/06/2015 (40)	22/07/2015 (41)
Golden Rove	2011	G	08/03/2011 (40)	11/04/2011 (40)	05/05/2011 (40)	06/06/2011 (40)	06/07/2011 (50)
	2012	2HG	09/03/2012 (80)	17/04/2012 (40)			
	2013	HG	10/04/2013 (87)	21/05/2013 (24)	12/06/2013 (41)		
	2014	G	28/04/2014 (40)	20/05/2014 (39)	26/06/2014 (39)	21/07/2014 (41)	
	2015	HG	10/04/2015 (43)	15/05/2015 (41)	16/06/2015 (39)	29/06/2015 (78)	

Table 4. *Fertilizer resource use efficiency. Annual harvest product per annual N applied or excreted between 3 grazed fields. LS=Longlands South, DN=Dairy North, GR=Golden Rove.

	LS $g\ m^{-2}: g\ m^{-2}$ Biomass: Applied N	DN $g\ m^{-2}: g\ m^{-2}$ Biomass: Applied N	GR $g\ m^{-2}: g\ m^{-2}$ Biomass: Applied N
2011	21.9	32.3	16.5
2012	47.6	55.8	65.3
2013	48.4	54.2	39.2
2014	58.7	115.4	44.3
2015	56.0	38.6	78.0
AVG	46.5 [5.8**]	59.2 [7.4**]	48.6 [6.0**]

*Fertilizer resource use efficiency in this study is the $g\ m^{-2}$ of harvest product per $g\ m^{-2}$ of nitrogen applied from fertiliser and excreta, where harvest product is defined as (a) annual aboveground biomass harvested and grazed (mixed annual management), or (b) **in square brackets, the live-weight gain of stock that the biomass would support. This is based on the average feed conversion ratio of 8 kg dry matter per kg live weight gain (Eblex sheep BRP manual 5, 2014). 44% of the sward’s dry matter biomass is carbon, and is used to convert model output of carbon to biomass.

Table 5. N_2O emission factors (referred to below as EFs, kg N_2O-N per kg fertilizer applied) mean and standard deviation, for grassland aggregated from fertilizer and grazed returns, simulated (a) annually from validated model by field and year for current climate, and (b) 30-year mean for climate scenarios. LS=Longlands South, DN=Dairy North, GR=Golden Rove.

(a)

Year	Mean Max Temp	Mean Min Temp	Mean Temp	Total Precip	LS EF	DN EF	GR EF
2011	13.98	7.32	10.65	834	0.025	0.028	0.040
2012	13.08	6.76	9.92	1229	0.039	0.046	0.033
2013	13.07	6.52	9.79	968	0.026	0.036	0.018
2014	14.45	7.60	11.02	1184	0.031	0.060	0.054
2015	13.58	7.26	10.42	933	0.036	0.035	0.028
Mean	13.63	7.09	10.36	1030	0.031	0.041	0.029
SD	0.6	0.4	0.5	169	0.006	0.013	0.009

(b)

Year	Mean Max Temp	Mean Min Temp	Mean Temp	Total Precip	LS EF	DN EF	GR EF
Baseline scenario 30 yr mean (SD)	12.8 (0.2)	5.8 (0.2)	9.3 (0.2)	1038 (123.1)	0.056 (1.53)	0.075 (1.7)	0.045 (1.9)
Medium emission 2080s 30 yr mean (SD)	16.4 (0.2)	9.0 (0.2)	12.7 (0.2)	1041 (123.3)	0.059 (1.45)	0.076 (1.7)	0.048 (2.0)
High. emission 2080s 30 yr mean (SD)	17.5 (0.2)	10.0 (0.1)	13.8 (0.2)	1025 (118.5)	0.059 (1.44)	0.078 (1.8)	0.048 (2.1)

Table 6. Metrics between three grazed fields growing *Lolium perenne* for nitrous oxide (N_2O-N) per unit product, (a) simulated for 2011-2015, where the product is grass biomass or, in square brackets the live-weight gain of lamb**, and (b) simulated 30-year mean results for climate scenarios. LS=Longlands South, DN=Dairy North, GR=Golden Rove.

(a)

	Mean Temp	Total Precip	LS N_2O-N:biomass g m^{-2}: g m^{-2}	DN N_2O-N:biomass g m^{-2}: g m^{-2}	GR N_2O-N:biomass g m^{-2}: g m^{-2}
2011	10.65	834.80	0.003 [0.024]	0.002 [0.016]	0.003 [0.024]
2012	9.92	1229.30	0.002 [0.016]	0.002 [0.016]	0.001 [0.008]
2013	9.79	968.70	0.001 [0.008]	0.001 [0.008]	0.001 [0.008]
2014	11.02	1184.00	0.001 [0.008]	0.001 [0.008]	0.001 [0.008]
2015	10.42	933.00	0.001 [0.008]	0.002 [0.016]	0.001 [0.008]
AVG	10.36	1029.96	0.002 [0.016]	0.002 [0.016]	0.002 [0.016]

(b)

	N_2O-N:biomass g m^{-2}: g m^{-2}	N_2O-N:biomass g m^{-2}: g m^{-2}	N_2O-N:biomass g m^{-2}: g m^{-2}
Baseline scenario 30 yr mean (SD)	0.0012 [0.0096] (0.0003)	0.0014 [0.0112] (0.0005)	0.0011 [0.0088] (0.0005)
Medium emission 2080s 30 yr mean (SD)	0.0012 [0.0096]* (0.0003)	0.0015 [0.012] (0.0005)	0.0011 [0.0088]* (0.0005)
High. emission 2080s 30 yr mean (SD)	0.0012 [0.0096]* (0.0003)	0.0016 [0.0128] (0.0006)	0.0012 [0.0096] (0.0005)

*both biomass and annual N_2O both increased under a warmer climate, retaining the same N_2O-N per unit product

** based on average feed conversion of 8 kg DM per kg live weight gain (Eblex sheep BRP manual 5, 2014).

Table 7. Metrics between three grazed fields growing *Lolium perenne* for leached inorganic nitrogen per unit product, (a) simulated for 2011-2015, where the product is grass biomass or, in square brackets the live-weight gain of lamb**, and (b) simulated 30-year mean results for climate scenarios. LS=Longlands South, DN=Dairy North, GR=Golden Rove.

(a)

	Mean Temp	Total Precip	LS Nleach:biomass $g\ m^{-2}$: $g\ m^{-2}$	DN Nleach:biomass $g\ m^{-2}$: $g\ m^{-2}$	GR Nleach:biomass $g\ m^{-2}$: $g\ m^{-2}$
2011	10.65	834.80	0.008 [0.064]	0.0014 [0.011]	0.0114 [0.091]
2012	9.92	1229.30	0.003 [0.024]	0.0017 [0.014]	0.0020 [0.016]
2013	9.79	968.70	0.004 [0.032]	0.0023 [0.018]	0.0013 [0.010]
2014	11.02	1184.00	0.003 [0.024]	0.0005 [0.004]	0.0018 [0.014]
2015	10.42	933.00	0.003 [0.024]	0.0065 [0.052]	0.0014 [0.011]
AVG	10.36	1029.96	0.004 [0.032]	0.0025 [0.016]	0.0036 [0.029]

(b)

	Nleach:biomass $g\ m^{-2}$: $g\ m^{-2}$	Nleach:biomass $g\ m^{-2}$: $g\ m^{-2}$	Nleach:biomass $g\ m^{-2}$: $g\ m^{-2}$
Baseline scenario 30 yr mean (SD)	0.0039 [0.0312] (0.0015)	0.0042 [0.0336] (0.0011)	0.0031 [0.0248] (0.0016)
Medium emission 2080s 30 yr mean (SD)	0.0041 [0.0328]* (0.0016)	0.0042 [0.0336] (0.0011)	0.0033 [0.0264]* (0.0015)
High. emission 2080s 30 yr mean (SD)	0.0039* (0.0015)	0.0040 [0.0320] (0.0013)	0.0033 [0.0264] (0.0015)

* both biomass and annual N_2O both increased under a warmer climate, retaining the same N_2O-N per unit product

** based on average feed conversion of 8 kg DM per kg live weight gain (Eblex sheep BRP manual 5, 2104).

Highlights:

- Provides yield-nitrogen metrics for ryegrass sheep pastures
- Combination of climate, sensor and sampling data applied to agri-system modelling
- Highest resource use efficiency coincides with lowest leaching per unit product
- N_2O per unit biomass significantly lower for silage & grazing than grazing only
- Several related metrics reveal info about the system, hidden by using one metric

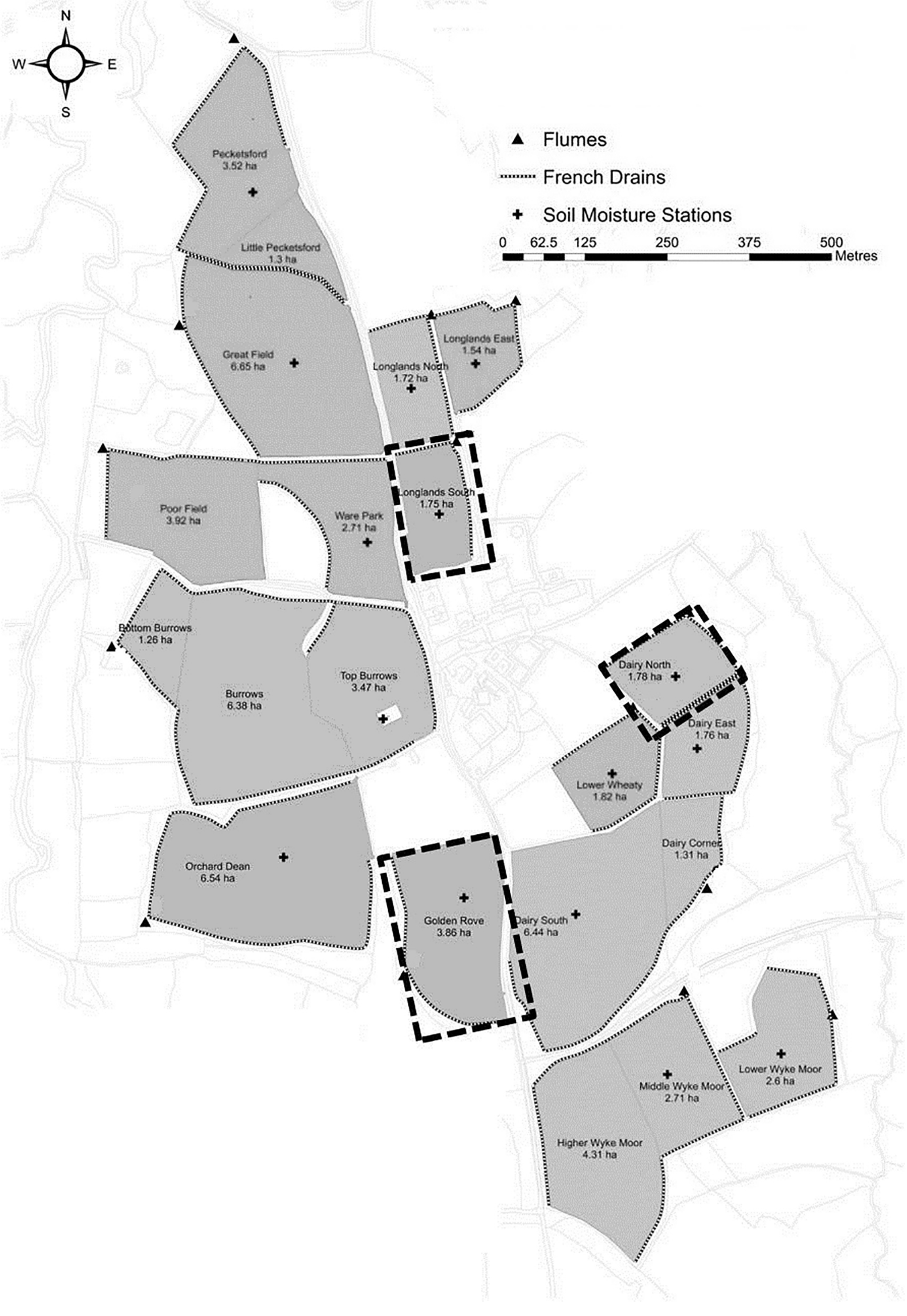
N
W
E
S
Flumes
French Drains
Soil Moisture Stations
0
62.5
125
250
375
500
Metres
Pecketsford 3.52 ha
Little Pecketsford 1.3 ha
Great Field 6.65 ha
Longlands North 1.72 ha
Longlands East 1.54 ha
Poor Field 3.92 ha
Ware Park 2.71 ha
Longlands South 1.75 ha
Bottom Burrows 1.26 ha
Burrows 6.38 ha
Top Burrows 3.47 ha
Dairy North 1.78 ha
Dairy East 1.76 ha
Lower Wheaty 1.82 ha
Dairy Corner 1.31 ha
Orchard Dean 6.54 ha
Golden Rove 3.86 ha
Dairy South 6.44 ha
Middle Wyke Moor 2.71 ha
Lower Wyke Moor 2.6 ha
Higher Wyke Moor 4.31 ha

Figure 1

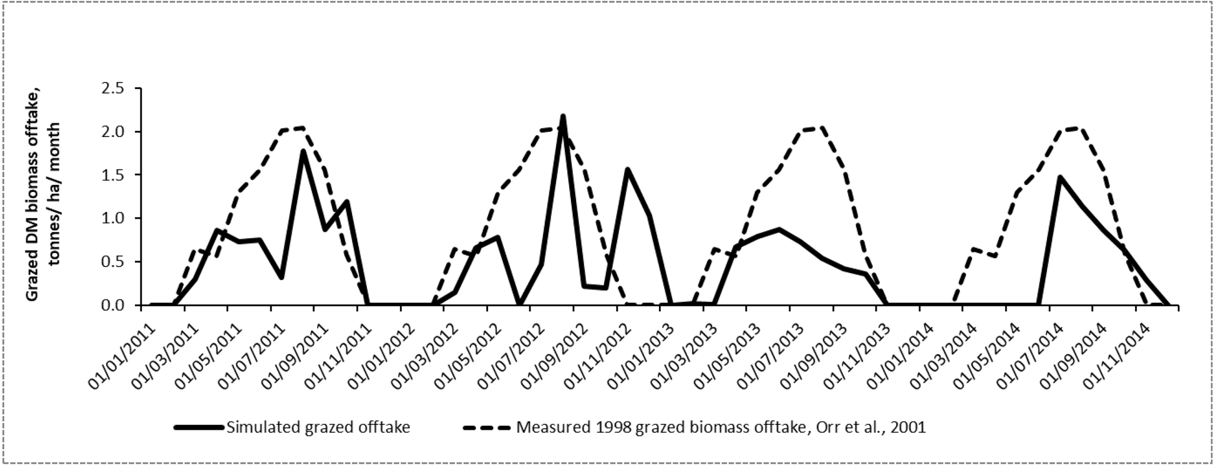
Grazed DM biomass offtake, tonnes/ ha/ month
2.5
2.0
1.5
1.0
0.5
0.0
01/01/2011
01/03/2011
01/05/2011
01/07/2011
01/09/2011
01/11/2011
01/01/2012
01/03/2012
01/05/2012
01/07/2012
01/09/2012
01/11/2012
01/01/2013
01/03/2013
01/05/2013
01/07/2013
01/09/2013
01/11/2013
01/01/2014
01/03/2014
01/05/2014
01/07/2014
01/09/2014
01/11/2014
Simulated grazed offtake
Measured 1998 grazed biomass offtake, Orr et al., 2001

Figure 2

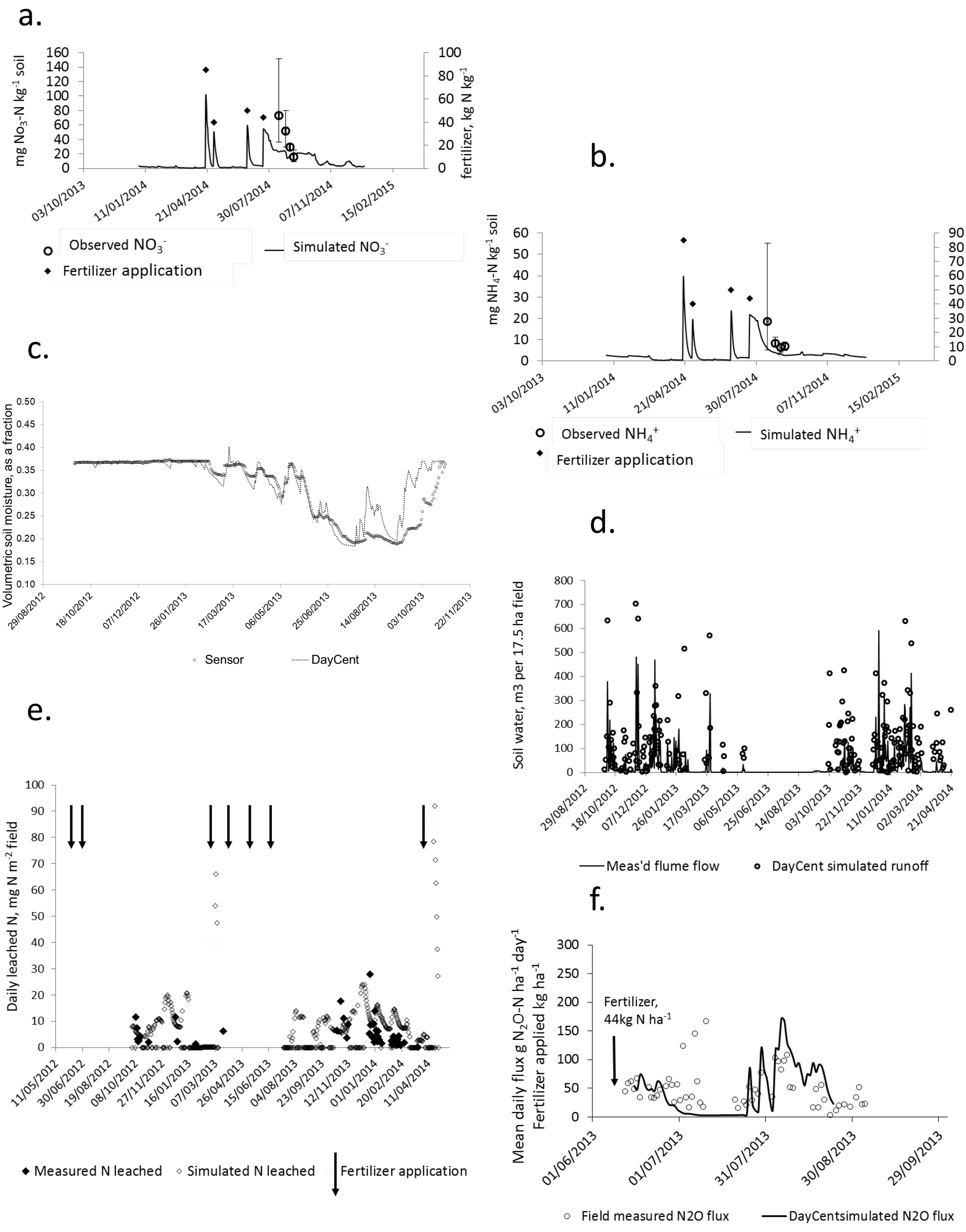
a.
mg No$_3$-N kg^{-1} soil
fertilizer, kg N kg^{-1}
0
20
40
60
80
100
120
140
160
0
20
40
60
80
100
03/10/2013
11/01/2014
21/04/2014
30/07/2014
07/11/2014
15/02/2015
Observed NO$_3^-$
Fertilizer application
Simulated NO$_3^-$
b.
mg NH$_4$-N kg^{-1} soil
Fertilizer, kg N kg^{-1}
0
10
20
30
40
50
60
0
10
20
30
40
50
60
70
80
90
03/10/2013
11/01/2014
21/04/2014
30/07/2014
07/11/2014
15/02/2015
Observed NH$_4^+$
Fertilizer application
Simulated NH$_4^+$
c.
Volumetric soil moisture, as a fraction
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50
29/08/2012
18/10/2012
07/12/2012
26/01/2013
17/03/2013
06/05/2013
25/06/2013
14/08/2013
03/10/2013
22/11/2013
Sensor
DayCent
d.
Soil water, m3 per 17.5 ha field
0
100
200
300
400
500
600
700
800
29/08/2012
18/10/2012
07/12/2012
26/01/2013
17/03/2013
06/05/2013
25/06/2013
14/08/2013
03/10/2013
22/11/2013
11/01/2014
02/03/2014
21/04/2014
Meas'd flume flow
DayCent simulated runoff
e.
Daily leached N, mg N m^{-2} field
0
10
20
30
40
50
60
70
80
90
100
11/05/2012
30/06/2012
19/08/2012
08/10/2012
27/11/2012
16/01/2013
07/03/2013
26/04/2013
15/06/2013
04/08/2013
23/09/2013
12/11/2013
01/01/2014
20/02/2014
11/04/2014
Measured N leached
Simulated N leached
Fertilizer application
f.
Mean daily flux g N$_2$O-N ha^{-1} day^{-1}
Fertilizer applied kg ha^{-1}
0
50
100
150
200
250
300
Fertilizer, 44kg N ha^{-1}
01/06/2013
01/07/2013
31/07/2013
30/08/2013
29/09/2013
Field measured N2O flux
DayCentsimulated N2O flux

Figure 3

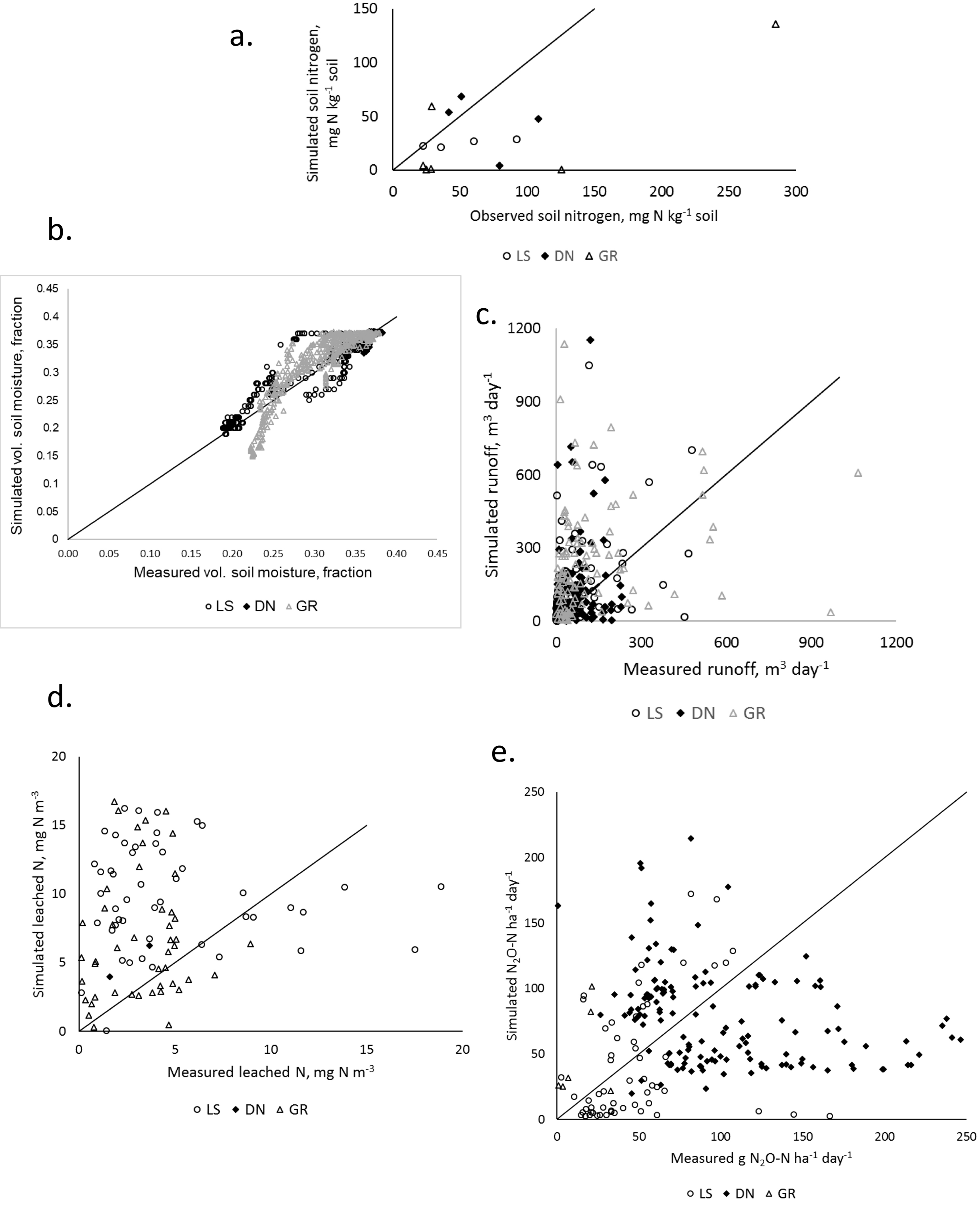
a.
Simulated soil nitrogen, mg N kg-1 soil
Observed soil nitrogen, mg N kg-1 soil
0
50
100
150
200
250
300
○ LS ◆ DN △ GR
b.
Simulated vol. soil moisture, fraction
Measured vol. soil moisture, fraction
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
○ LS ◆ DN △ GR
c.
Simulated runoff, m3 day-1
Measured runoff, m3 day-1
0
300
600
900
1200
○ LS ◆ DN △ GR
d.
Simulated leached N, mg N m-3
Measured leached N, mg N m-3
0
5
10
15
20
○ LS ◆ DN △ GR
e.
Simulated N2O-N ha-1 day-1
Measured g N2O-N ha-1 day-1
0
50
100
150
200
250
○ LS ◆ DN △ GR

Figure 4

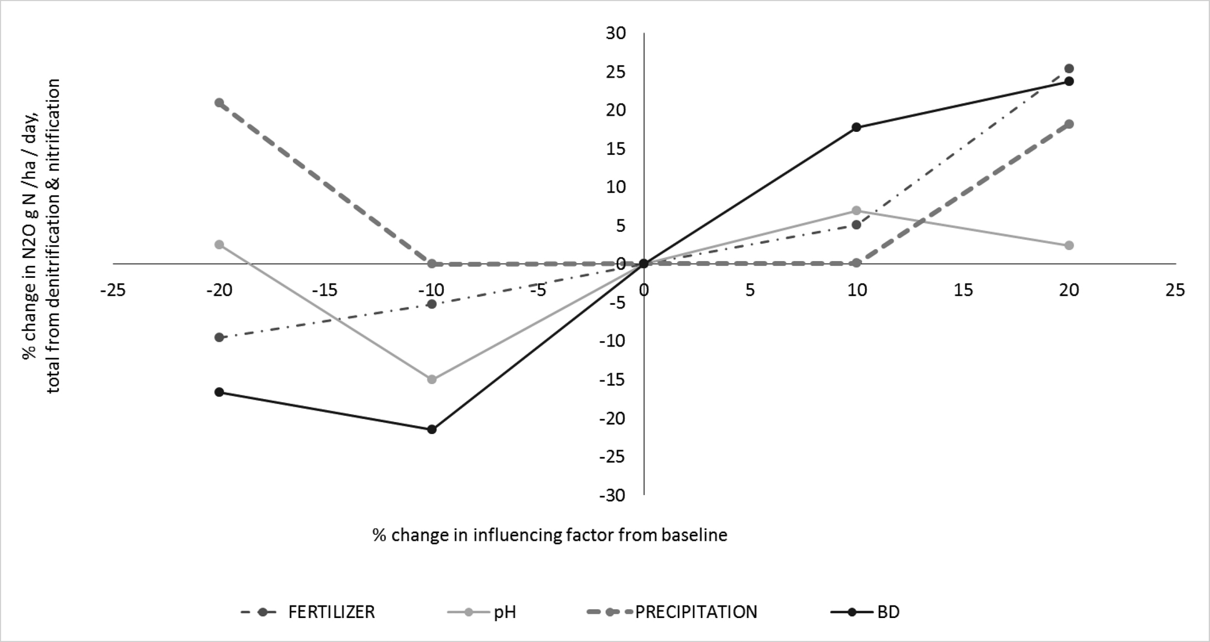
% change in N2O g N /ha / day,
total from denitrification & nitrification
% change in influencing factor from baseline
30
25
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
FERTILIZER
pH
PRECIPITATION
BD

Figure 5