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Research article

Scenario based modelling approach to inform the spatial refinement of nitrogen management strategies for improving nitrogen use efficiency in Irish grasslands

Sudipto Bhowmik [a,b,*], Rowan Fealy [a], David Wall [b], Réamonn M. Fealy [c], Lilian O'Sullivan [b]

[a] ICARUS & Department of Geography, Maynooth University, Maynooth, Kildare, Ireland
[b] Crops, Environment & Land Use Programme, Teagasc, Johnstown Castle, Co. Wexford, Ireland
[c] Rural Economy and Development Programme, Teagasc, Ashtown, Dublin, Ireland

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ABSTRACT

Current national nitrogen (N) management policies in Ireland, such as the Green Book (GB) and the Fifth Nitrates Action Programme (NAP), do not explicitly consider geographical factors (e.g. weather, soils) that influence nitrogen uptake and loss and which could lead to improved on-farm sustainability, in line with the goals of 4R Nutrient Stewardship (4RNS). One approach to address this is to classify the landscape by soil and climatic indicators of yield and N loss (Group 1 Variables -regional); this could be refined with more targeted monitoring in zones where a reduction of yield and N loss occurs under a reduced N input regime (Group 2 Variables - locale specific), required to identify more local context-specific factors. Here, we employed the DNDC (*DeNitrification DeComposition*) model to identify Group 1 and Group 2 Variables for grass yield and N loss, through scenario analysis for three Irish grassland sites for year 2019, with local model parameterisation and a suite of minimum inputs required for reliable performance - identified from existing literature. The study sites were a sandy loam (JCSL) and a loam soil (JCL) site at Johnstown Castle (lower average annual rainfall and daily temperature) and a sandy loam (MP) site at Moorepark. While both MP and JCSL had sandy loam soil, MP a higher bulk density (BD), pH and water filled pore spaces (WFPS) at field capacity (FC) and wilting point (WP) but lower soil organic carbon (SOC) and clay content than JCSL. Based on the scenarios simulated, the NAP resulted in a lower simulated yield (−4.98 % to −15.62 %) and a reduction in ammonia (NH_3) volatilisation (−29.40 % to −30.35 %), nitrous oxide (N_2O) emissions (−30.49 to −35.15 %) and nitrate (NO_3^-) leaching (−55.51 % to −61.38 %). Both Group 1 and 2 Variables for annual yield and N_2O emissions were soil sand content, BD, SOC and for NH_3 volatilisation, annual rainfall and average annual temperature, for both GB and NAP. The Group 2 Variables for NO_3^- leaching were soil sand and clay content, pH, annual rainfall and average annual temperature; corresponding Group 1 Variables were found to vary under both GB and NAP.

1. Introduction

Managing grasslands for livestock production is the most important agricultural land use practice in Ireland. It accounts for over 92 % of national agricultural land use and is dominated by perennial ryegrass (O'Donovan et al., 2021). Nitrogen (N) application in Irish grasslands is commonly supplied through the application of inorganic N fertilisers, such as urea and Calcium Ammonium Nitrate (CAN), along with organic fertilisers including farmyard manure and slurry (Gebremichael et al., 2021; Mihailescu et al., 2014). Of the N applied, only an estimated 25 % is recovered (Teagasc, 2021), indicating that the remaining 75 % is susceptible to loss, mainly through - ammonia (NH_3) volatilisation, nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching (e.g. Hoekstra et al., 2020; van Beek et al., 2008; Woodmansee et al., 1981). N loss represents both an economic and productivity loss to the farmer but also degrades environmental quality through air pollution (NH_3), climate change and ozone layer depletion (N_2O), as well as ground and surface water quality (high NO_3^- concentrations) resulting in the eutrophication of water bodies and soil acidification etc. (e.g. Burchill et al., 2017; de Vries, 2021; Ferm, 1998; Giordano et al., 2021; Pittelkow et al., 2013; Stark and Richards, 2008; van Grinsven et al., 2013).

The European Union (EU) has set ambitious targets to achieve

* Corresponding author. ICARUS & Department of Geography, Maynooth University, Maynooth, Kildare, Ireland.
E-mail address: sudipto.soilres@gmail.com (S. Bhowmik).

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climate neutrality in the EU through the European Green Deal, under which the Farm to Fork Strategy seeks to reduce agriculture driven environmental degradation (DGE, EC, 2022; EC, 2019). The goals of the Farm to Fork Strategy have led to the development and application of the Common Agricultural Policy (CAP) measures across EU member states, that seek to reduce N loss from agriculture through more sustainable land management practices (EC, 2020; Wrzaszcz and Prandecki, 2020; EC, 2023). Additionally, the EU Nitrates Directive focuses on monitoring and preventing the pollution of surface and ground water by NO_3^- from agriculture (EPC, 1991). Ireland, as an EU member state, has developed national policies that aim to limit N fertiliser application to reduce N loss while improving overall productivity of grasslands. The current agricultural goals set within the national Food Wise 2025 programme aim to utilise more sustainable agricultural practices in order to increase primary productivity in Ireland by €10 billion from the levels of 2015 (DAFM, 2021), while at the same time, Ireland's Climate Action Plan 2023 aims to reduce N loss through NH_3 volatilisation, N_2O emissions and NO_3^- leaching (DECC, 2023), in line with international obligations on greenhouse gas emissions.

In line with these goals, national agricultural policies, particularly those with a focus on delivering improved grassland management practices, have been developed and modified over time. The Green Book (GB), published in 2020 (Wall and Plunkett, 2020), provides nutrient advice, including annual maximum N fertiliser application guidelines for different stocking rate bands and recommends splits of N application based on the phases of grass growth throughout the year. These guidelines, in line with the EU Nitrates Directive - National Action Programme regulations, limit the maximum N fertiliser application rate to 279 kg N/ha for stocking rates above 2.47 LU/ha (LU = livestock unit) (that can supply more than 210 kg N/ha in organic form) (Wall and Plunkett, 2020). More recently, the Department of Agriculture, Food and the Marine (DAFM) implemented a modified Nitrates Regulation policy under the Fifth Nitrates Action Programme (NAP) that categorised dairy livestock into bands according to the potential N content in excreta, estimated based on herd milk production (DAFM, 2023). This guideline provides information on the maximum N fertiliser application for different stocking rates and sets a lower maximum limit of annual N fertiliser application to 225 kg N/ha, once a herd reaches the capacity of supplying 250 kg/ha of organic N. It also classified the country into four zones based on the storage periods of livestock manure and includes prohibition periods for nutrient application (DAFM, 2023). A more recent policy update to the Nitrates Derogation strategy reduced the maximum permissible stocking rate to 220 kg of organic N/ha (Callaghan, 2023).

Currently, dairy farms in Ireland typically achieve 50–60 % of their potential grass yield (O'Donovan et al., 2021). Despite this, between 1990 and 2022, NH_3 volatilisation increased by 12.4 %, while N_2O emissions decreased by 8.8 %, with an increase evident in N_2O emissions between 2015 and 2022 - driven by an expansion of the dairy sector and increased N fertiliser use (EPA, 2022; EPA, n.d.). High NO_3^- concentrations have also been observed across 40 % of monitored river sites and in 20 % of estuarine and coastal water bodies (EPA, 2023). Consequently, there is an urgent need to improve N use efficiency (NUE) through more sustainable land management practices (Teagasc, 2021) to meet both the productivity targets and environmental goals set within national and international policy (e.g. NAP 2022–2025) (DHLGH and DAFM, 2022). Improved NUE and a reduction of N loss can potentially be achieved by determining the *right source*, *right rate*, *right time*, and *right place* of N application, the basic objectives of 4R Nutrient Stewardship (4RNS) (Bryla, 2020; Fixen, 2020). Exploring the impact of both spatial and temporal variations in N dynamics under different weather and soil conditions in managed grasslands could inform the development of more geographically refined N management plans required to meet these objectives (Sarkar et al., 2017; Shanahan et al., 2008; Varallyay, 1994; Wu and Ma, 2015).

Modelling approaches, that incorporate soil, weather and management data to simulate key soil N-dynamics processes – such as, mineralisation, leaching, volatilisation, nitrification, denitrification, uptake and biological N fixation (BNF) – are useful tools to explore variations in N dynamics under diverse environmental and management conditions, even though their robust application is often restricted due to limited data availability (e.g. Cannavo et al., 2008; Giltrap et al., 2010; Haraldsson and Sverdrup, 2013; Patil, 2009). The *DeNitrification-DeComposition* model (DNDC) is one of the few biogeochemical models that captures all key soil processes related to N dynamics reducing the assumptions made on the impact of these processes (Cannavo et al., 2008). Besides, DNDC output contains details on N dynamics that include yield, NH_3 volatilisation, N_2O emissions and NO_3^- leaching, that are most relevant for grassland management (Cannavo et al., 2008; Hoekstra et al., 2020; ISEOS, UNH, 2012; van Beek et al., 2008).

Previous studies performed in Irish grasslands used different versions of DNDC and mainly focused on N_2O emissions, soil organic carbon (SOC) and carbon dioxide (CO_2) emissions (e.g. Abdalla et al., 2009; Abdalla et al., 2010; Abdalla et al., 2011; Hsieh et al., 2005; Khalil et al., 2020; Li et al., 2011; Rafique et al., 2011; Zimmermann et al., 2018). Studies performed using the UK-DNDC version in the United Kingdom, which also falls in the *Atlantic Zone* for grass production, similar to Ireland, (Lesschen et al., 2014), also primarily focused on N_2O emissions (e.g. Cardenas et al., 2013; Shah et al., 2020; Shen et al., 2018). However, in these studies, an explicit parametrisation and validation of the model for perennial ryegrass sites, the dominant grass species in Irish grasslands (O'Donovan et al., 2021), and local background atmospheric conditions, validation of yield and NH_3 volatilisation and/or NO_3^- leaching remain absent – relevant for confidence in model estimated surplus N and overall N dynamics (Zhang et al., 2015). More recent studies by Bhowmik (2025), using version 9.5 of DNDC, produced reliable estimates of yield and N loss through NH_3 volatilisation and N_2O emissions following parameterisation of DNDC for phenology (biomass fraction and its carbon to N ratio, thermal degree days of maturity, water requirement) of perennial ryegrass and background atmospheric conditions (atmospheric NH_3 and CO_2 concentrations, rates of annual increase of CO_2 and N concentration in rainfall). These studies showed that along with the mandatory soil inputs (textural class, SOC, soil pH), site-specific inputs are required on soil bulk density (BD), clay content and water filled pore spaces (WFPS) at field capacity (FC) and wilting point (WP). Therefore, it is assumed that if the model can generate reliable estimates of annual NH_3 volatilisation and N_2O emissions for grassland, then the estimated NO_3^- leaching for grasslands should also be reliable – since these three are the major pathways of N loss from grasslands (Hoekstra et al., 2020; van Beek et al., 2008; Woodmansee et al., 1981). Further, among the models with similar capacity for simulating soil N dynamics under specific management regimes, e.g. DayCent, ECOSSE, DNDC, only the DNDC model explicitly accounts for the microbial mediation of N dynamics (Abdalla et al., 2016, 2023; Grant et al., 2016; Zimmermann et al., 2018) increasing the utility of DNDC for our study to account for the impact of soil and weather conditions on ammonification, nitrification and denitrification (Jeannotte, 2014; Rascio and La Rocca, 2013; Sahrawat, 2008; Tiedje, 2014).

The aim of this research was to explore the potential impact of soil and management variability on yield and N loss across selected sites under existing N fertiliser and grazing regimes. The aim was not to evaluate DNDC as this has been undertaken elsewhere, but to evaluate the potential to use a model based approach that could inform more refined N management. We used DNDC (v 9.5) to explore annual yield and N loss through annual NH_3 volatilisation, N_2O emissions and NO_3^- leaching for a selection of grassland sites, where suitable data was available for the required suite of input variables (Bhowmik, 2025). Scenario analysis for two different intensive management scenarios are targeted, as follows: 1) N inputs based on the advice provided in the latest edition of the GB (Wall and Plunkett, 2020); and, 2) based upon the regulations established in the NAP on targeted stocking rates

(DAFM, 2023). The objective was to explore if national level advice and policies for improved N management can support optimum productivity and a reduction of N loss (Giltrap et al., 2010), across spatially diverse farms, and if not, then what are the key drivers that need to be considered to refine such policies; recognising environmental and meteorological constraints. The ultimate goal was to develop a replicable strategy to use the DNDC model to explore the potential impact of N management policies and strategies and to inform more spatially refined advice and policy to deliver more sustainable N management, across scales.

2. Methods

2.1. Site locations

Three grassland sites were chosen as sites for this study largely based on the availability of data but also considering the variability of soil and climatic conditions. The sites were from two locations (Fig. 1), a moderately coarse sandy loam soil site at Moorepark (MP) (52.2°N 8.3°W), located in County Cork, with the remaining two sites located at Johnstown Caste (JC), County Wexford (52.3°N 6.5°W), one of which has moderately coarse sandy loam soil (JCSL) while the other has a medium textured loam soil (JCL) (AA-FC, 2009; Zimmermann et al., 2018). For the selected experimental year (2019) for which in-situ evaluation data was available, the annual average daily temperature at MP and JC was 10.28^{0}C and 8.55^{0}C respectively. The annual rainfall at MP and JC over the analysis period was 1084 mm and 1062 mm respectively, as calculated from the corresponding weather data (Met Éireann, n.d.). The three sites, located in the southern part of Ireland, display small differences in annual meteorological conditions for 2019. However, these differences can be important to understand the drivers of variation of N dynamics across the sites, as all three studied forms of N

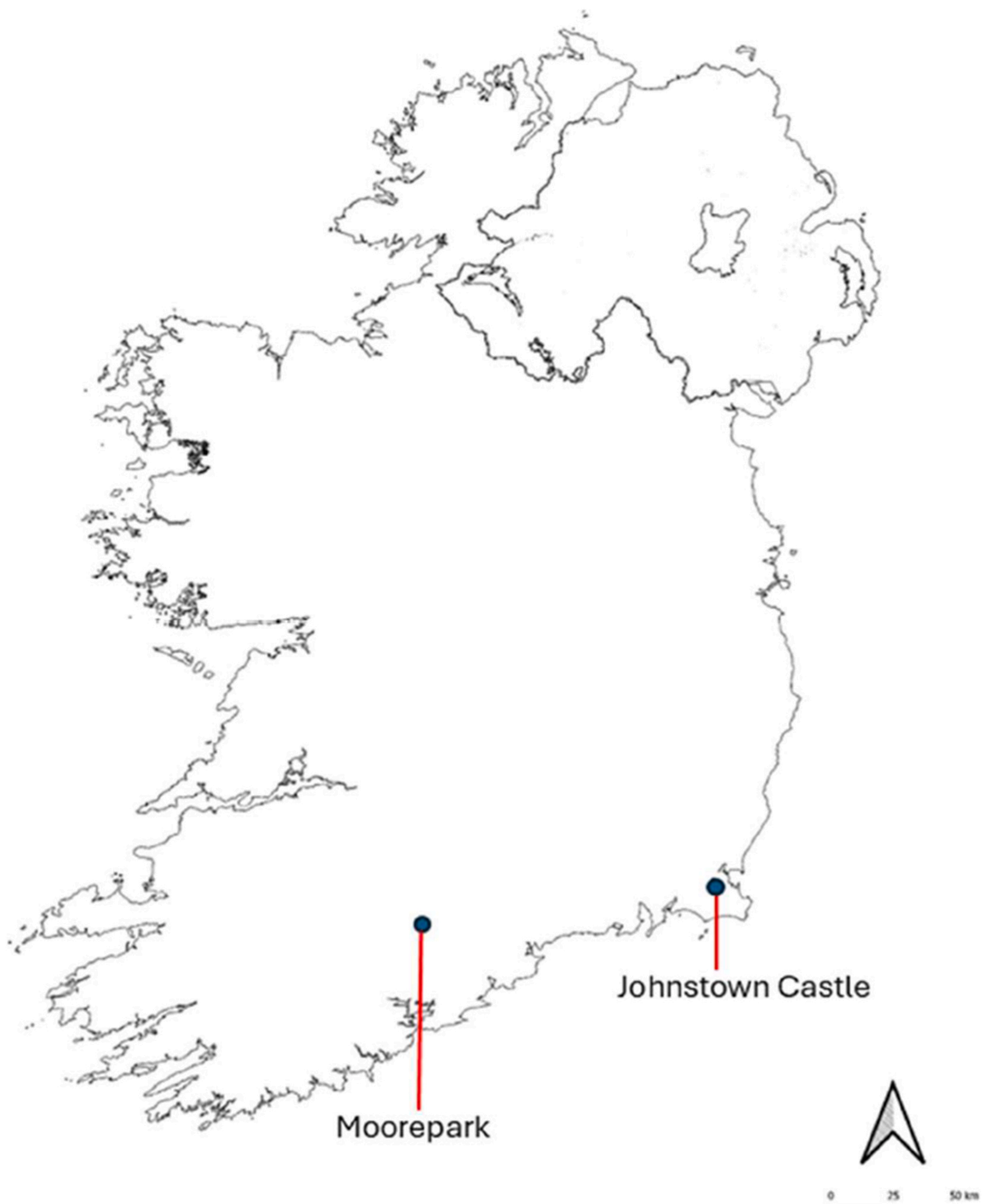

Fig. 1. Locations of the Moorepark and Johnstown Castle.

loss – NH_3 volatilisation, N_2O emissions and NO_3^- leaching - are regulated by meteorological conditions (e.g. Bouwmeester et al., 1985; Griffis et al., 2017; Jabloun et al., 2015).

2.2. Data

Daily maximum and minimum temperature, rainfall and solar radiation were obtained for each site for the year 2019 from Met Éireann (n.d.) (the Irish national meteorological agency) (https://www.met.ie/climate/available-data/historical-data) from meteorological stations located in Moorepark and Johnstown Castle. Daily precipitation (mm) and solar radiation (J/cm^2) data were converted to cm and MJ/m^2 (ISEOS, UNH, 2012), respectively. For atmospheric NH_3 concentration and the N concentration in rainfall, available data was obtained from environmental monitoring stations in close proximity to the study sites from Doyle et al. (2017) and Jordan (1997), respectively (Table 1). Zimmermann et al. (2018) reported on the soil physicochemical properties at MP and JC, determined as the minimum required site-specific inputs by Bhowmik (2025), including the corresponding soil volumetric water content at FC and WP. The corresponding WFPS at FC and WP for the sites were derived using the methods from Franzluebbers (1999) (Table 1). As the pH of the soils at these sites was below 6.5 (Zimmermann et al., 2018), the total carbon in the soil was considered as SOC at both MP and JC (Franzluebbers and Stuedemann, 2002). The threshold for thermal degree days at maturity (TDD) for vegetative growth of perennial ryegrass was unavailable at the sites. The TDD for each site, was calculated using the corresponding Met Éireann weather data (Met Éireann, n.d.). For both MP and JC, this was performed following the method of Hart et al. (2013). The whole year was considered as year-round vegetative growth of perennial ryegrass occurs in Ireland (Cappello et al., 2021; Wingler and Hennessy, 2016) (Table 1).

Two urea application scenarios, based on idealised intensive fertiliser application regimes, were designed for a stocking rate of 2.36 cows/ha, considering a herd of Band 3 (DAFM, 2023) cows that would supply 250 kg N/ha in organic form (Table 2), to maintain a stocking rate of 2.36 cows/ha, dry matter of 11.8 t/ha is required (O'Donovan, 2016). The N fertiliser application regimes under each scenario was spatially uniform across the studied sites. The first scenario, with a higher maximum N fertiliser input proposed for a stocking rate range of 2.35 to <2.47 cows/ha was based on the Green Book recommendations, henceforth referred to the GB regime (Wall and Plunkett, 2020). This scenario does not account for the recent limitations in annual N fertiliser application set by the banding of cows based on milk production (DAFM, 2023). The other regime assessed was a lower, yet still intensive, N fertiliser input scenario, based on the NAP 2022–2025, that sets a limit for the maximum N fertiliser application considering the limits set for Band 3 cows (DAFM, 2023), referred to as the NAP regime. The annual N fertiliser application was 26.5 % lower for the NAP regime than that recommended in the GB (DAFM, 2023; Wall and Plunkett, 2020). However, both application regimes are aspatial in nature, while fertiliser application dates were temporally uniform across the studied studies.

The grazing regime and stocking rate used for the simulation was spatially and temporally uniform across the studied sites. The first and last grazing dates (Table 2) were set according to the JC farm management records for 2019 and used for all sites, as the aim was to maintain a uniform grazing regime to focus solely on the impact of soil and weather on grass yield and N dynamics. Considering each soil dataset used in this study to be representative of a farm, it was assumed that the fertiliser application timing of day was performed after grazing animals have moved away from a paddock within a farm, thus no gaps were present within the entire annual period of grazing. The entire duration of this time period (days) was considered to be grazed, with no silage cutting events. The average grazing hours duration was set at 20 h/day throughout the grazing period (Byrne and Kiely, 2008). Splits of N fertiliser applications and application dates were derived according to the GB for both scenarios (Wall and Plunkett, 2020) and the application dates remained the same for each split of N fertiliser application under both scenarios. There was no silage harvest event included in any of the site simulations, considering the livestock was dependent entirely on grazing. However, inclusion of silage cutting activity information in DNDC does not affect the estimated grass growth, whereas it is also not a source of N or other nutrients unlike grazing (Kang et al., 2013; Saggar et al., 2007). Thus, the finding of this study would remain relevant for grasslands used for silage cutting also.

2.3. DNDC model: inputs and parameters

The DNDC model (v9.5) (Source: http://www.dndc.sr.unh.edu/) was used to simulate annual grass yield and annual NH_3 volatilisation, N_2O emissions and NO_3^- leaching (Gilhespy et al., 2014; Tang et al., 2024). A detailed description of the model and its inputs can be found in the work of Gilhespy et al. (2014) and in the model manual (ISEOS, UNH, 2012). Site-specific detailed inputs for each location on weather, soil physicochemical properties, background atmospheric NH_3 concentration, N concentration in rainfall, and TDD was employed for each site (Table 1). The management inputs for the high (GB) and modified (NAP) N fertiliser input scenarios for a fixed grazing regime were used for simulations as shown in Table 2. Other inputs for crop phenology and atmospheric conditions were kept fixed for all simulations as shown in Table 3.

2.4. Experimental design

Two case studies were designed to evaluate the GB and NAP N inputs scenarios across the selected sites on grass yield and N loss. For each case study, the inputs on soil conditions (except textural class for MP and JCSL) were different for each site, to reflect the site-specific conditions. For the two locations, JC and MP, the background atmospheric NH_3 concentration, N concentration in rainfall, TDD and daily weather were different and information representative of local conditions was used. Hence, weather and background atmospheric conditions were the same for the sites JCL and JCSL, both located in the JC farm, while these sites

Table 1
Site specific information.

Category	Farm	Moorepark	Johnstown Castle Dairy Farm		References
	Sites: Selected Paddocks	MP	JCSL	JCL	
Soil	Texture	Sandy loam	Sandy loam	Loam	Franzluebbers (1999);
	BD (g/cm$^{3)}$	1.205	1.11	1.27	Zimmermann et al. (2018)
	Clay (%)	13.8	13.9	14.4	
	pH	5.47	5.53	5.69	
	SOC (%)	2.99	3.14	2.78	
	WFPS at FC (%)	61.21	53.67	70.7	
	WFPS at WP (%)	30.94	25.79	38.9	
Background Atmospheric Conditions	Atmospheric NH_3 Concentration (μg/m^3)	2.04	2.83	2.83	Doyle et al. (2017);
	N concentration in Rainfall (mg N/l)	0.56	1.02	1.02	Jordan (1997)
Crop Phenology	TDD	3577	3871	3871	Hart et al. (2013); Met Éireann, n.d.

Table 2
Idealised Management Scenarios (Based on Maximum Permissible N Fertiliser Application under Two Different Guidelines) that are Uniform Across the Studies Sites for a Uniform Grazing Regime with Same Targeted Stocking Rate of 2.36 Cows Per Hectare).

	N Input Dates (Day/Month) for 2019			15/02	15/03	15/04	15/05	15/06	15/07	15/08
N Fertiliser Application Regimes	Case Study	Total N fertiliser (urea) according to	Maximum Permissible Fertiliser	Splits of Application (kg N/ha)						
	High N Fertiliser Input	Green Book (GB)	306 kg N/ha	31	54	54	56	37	37	37
	High N Fertiliser Input									
	Modified N Fertiliser Input	Fifth Nitrates Action Programme (NAP)	225 kg N/ha	23	40	40	41	27	27	27
	Modified N Fertiliser Input									
Grazing Regime	Stocking Rate 2.36 Cows/ha)	For both GB and NAP Regimes of N FertiliserApplication	Start: Month 1 Day 13 End: Month 12 Day 23							
Silage Harvest	None									

Table 3
Inputs on crop phenology for perennial ryegrass and atmospheric conditions.

Category	Variables	Modified	References
Crop Phenology	C/N ratio for seed/leaf/stem	19/19/19	Whitehead et al. (1990)
	C/N ratio for roots	23	
	N-fixation index (crop N/N from soil)	1	ISEOS, UNH (2012)
	Water demand (g water/g DM)	550	Byrne and Kiely (2008)
Atmospheric Conditions	Atmospheric background CO_2 concentration (ppm)	409.8	Ullas Krishnan and Jakka (2022)
	Annual rate of increase Atmospheric background CO_2 concentration (ppm)	2.3	Prasad et al. (2021)

differed in terms of the corresponding weather and atmospheric conditions from the site at MP. These inputs remained unchanged between the two case studies examined; the differences between the case studies relate to the amount of N fertiliser applied (urea) (Table 2).

2.5. Outcomes and evaluation metrics

For each simulation, the annual estimated grass yield was derived from the sum of the estimated yield of grain, leaf and stem in kg C/ha and converted to kg DM/ha (ISEOS, UNH, 2012), while the annual estimation of NH_3 volatilisation, N_2O emissions and NO_3^- leaching was generated by DNDC in kg N/ha. The estimated yield was compared with the desired yield of 11.8t, required to maintain a stocking rate of 2.36 cows/ha (O'Donovan, 2016) to determine whether the GB and modified NAP fertiliser input guidelines could sustain the required productivity target. The difference for each site for the estimated yield under each management regime and desired yield was calculated. Differences in the N management regime between the GB and NAP scenario - in terms of estimated annual yield, NH_3 volatilisation, N_2O emissions and NO_3^- leaching at each site - were calculated and reported as a percentage difference. These were compared to see if equivalent changes across the sites are achieved based upon a uniform reduction in N fertiliser inputs (i.e. from GB to NAP). Also, the rank order of physicochemical properties of soil and annual rainfall and temperature was compared with the order of variation of estimated annual grass yield and annual NH_3 volatilisation, N_2O emissions and NO_3^- leaching across the studied sites - to explore if they could explain any variations evident between the study sites.

3. Results

The estimated annual yield, for the year 2019, varied from 10,562.78 kg DM/ha at JCSL to 11,238.38 kg DM/ha JCL under Case Study 1 (GB regime) and from 8913.23 kg DM/ha at JCSL to 10,678.78 kg DM/ha at JCL under Case Study 2 (NAP regime) (Table 4; Fig. 2). An amount equivalent to or greater than the required 11.8 t/ha of DM was not achieved at any of the sites under any of the management regimes. The estimated annual NH_3 volatilisation varied from 147.31 kg N/ha at MP to 157.31 kg N/ha at JCSL under Case Study 1 and from 102.6 kg N/ha at MP to 111.06 kg N/ha at JCSL under Case Study 2 (Table 4; Fig. 2). Annual estimated N_2O emissions varied from 0.82 kg N/ha at JCSL to 1.65 kg N/ha at JCL under Case Study 1 and 0.57 kg N/ha at JCSL to 1.07 kg N/ha at JCL under Case Study 2 (Table 4; Fig. 2). The estimated annual NO_3^- leaching varied from 9.08 kg N/ha at JCL to 11.13 kg N/ha at JCSL under Case Study 1 and 3.97 kg N/ha at MP to 4.34 kg N/ha at JCSL under Case Study 2 (Table 4; Fig. 2).

The results of the simulations show the potential impact of spatial variations in soil and weather conditions on perennial ryegrass yield and N loss through key pathways, when the N fertiliser application rate and timing is uniform and the grazing regime is spatially and temporally uniform across the studied sites. From the results of this study, it was found that for both the GB and the NAP management regimes, the highest yield and annual N_2O emissions were estimated at JCL followed by MP and JCSL, whereas the highest annual NH_3 volatilisation was

Table 4
Variation of Estimated Annual Yield and Nitrogen Loss under High and Low N Fertiliser Input Scenarios and their Reduction under Reduction of Nitrogen Fertiliser Inputs from High to Low.

Scenario	Sites	Scenario (Case Studies)		Percent change (%) between GB and NAP
		Case Study 1	Case Study 2	
N Fertiliser Inputs		High (GB)	Modified (NAP)	
Annual Yield (kg DM/ha)	**MP**	11,054.4	10,334.45	−6.51
	JCSL	10,562.78	8913.23	−15.62
	JCL	11,238.38	10,678.78	−4.98
Annual Ammonia Volatilisation (kg N/ha)	**MP**	147.31	102.6	−30.35
	JCSL	157.31	111.06	−29.40
	JCL	148.83	104.6	−29.72
Annual Nitrous Oxide Emissions (kg N/ha)	**MP**	1.24	0.86	−30.65
	JCSL	0.82	0.57	−30.49
	JCL	1.65	1.07	−35.15
Annual Nitrate Leaching (kg N/ha)	**MP**	10.28	3.97	−61.38
	JCSL	11.13	4.34	−61.01
	JCL	9.08	4.04	−55.51

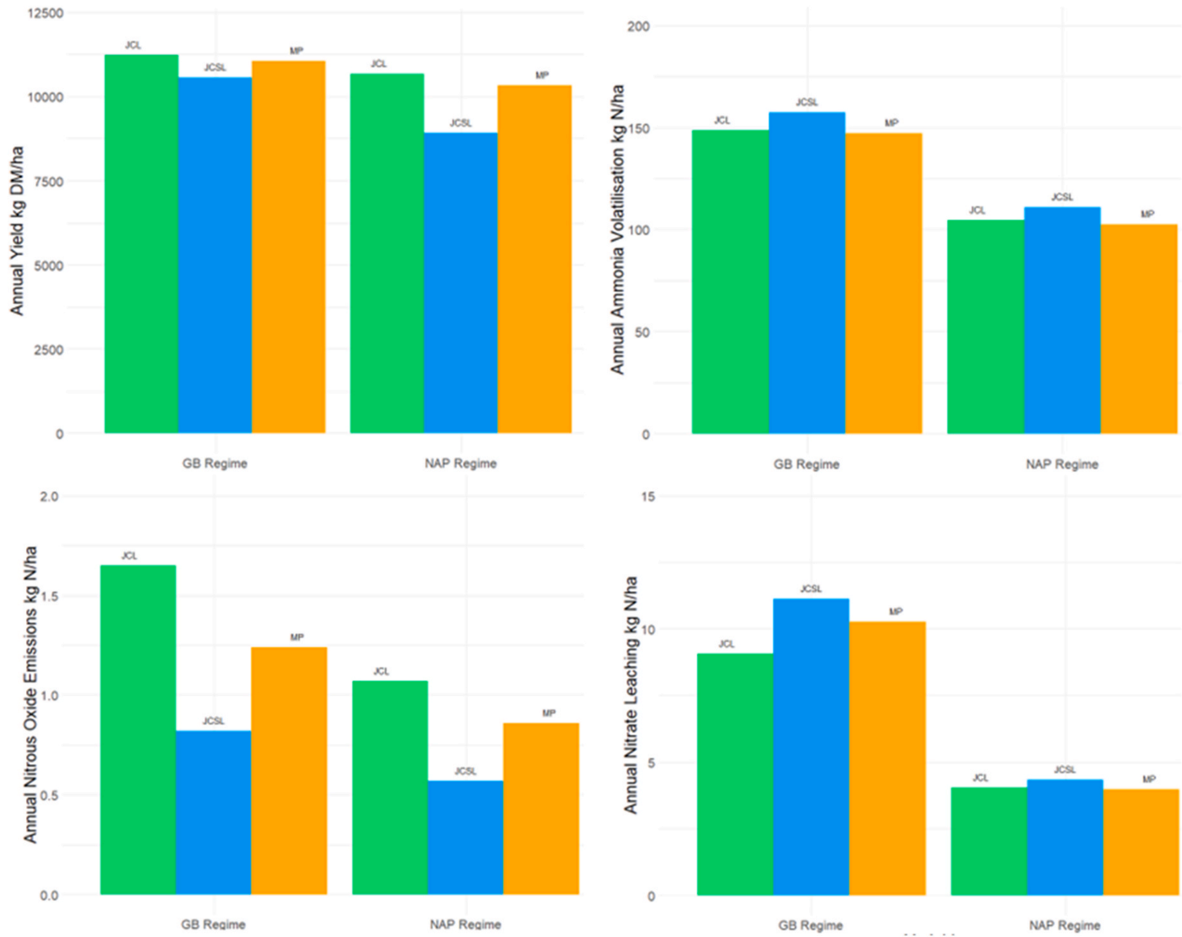

Fig. 2. Variation of annual yield of perennial ryegrass (top-left), ammonia (NH_3) volatilisation (top right), nitrous oxide (N_2O) emissions (bottom-left) and nitrate (NO_3^-) leaching (bottom-right) under GB Regime (higher N fertiliser input) and NAP Regime (lower N fertiliser input) across the studied sites.

estimated for JCSL, followed by JCL and MP. The higher estimated yield was associated with higher BD and WFPS at FC and WP and was also associated with lower SOC across the sites. It was also partially associated with the lower sand content in the soil, represented by loam texture at JCL. Annual N_2O emissions across sites, irrespective of the rate of N fertiliser application, were higher for soils with higher BD, WFPS at FC and WP. Difference between WFPS at FC and WP, indicating higher plant available water (Pragg et al., 2024), was also higher for sites with higher annual N_2O emissions. Higher annual N_2O emissions was also associated with sites with lower SOC and was partially aligned with lower sand

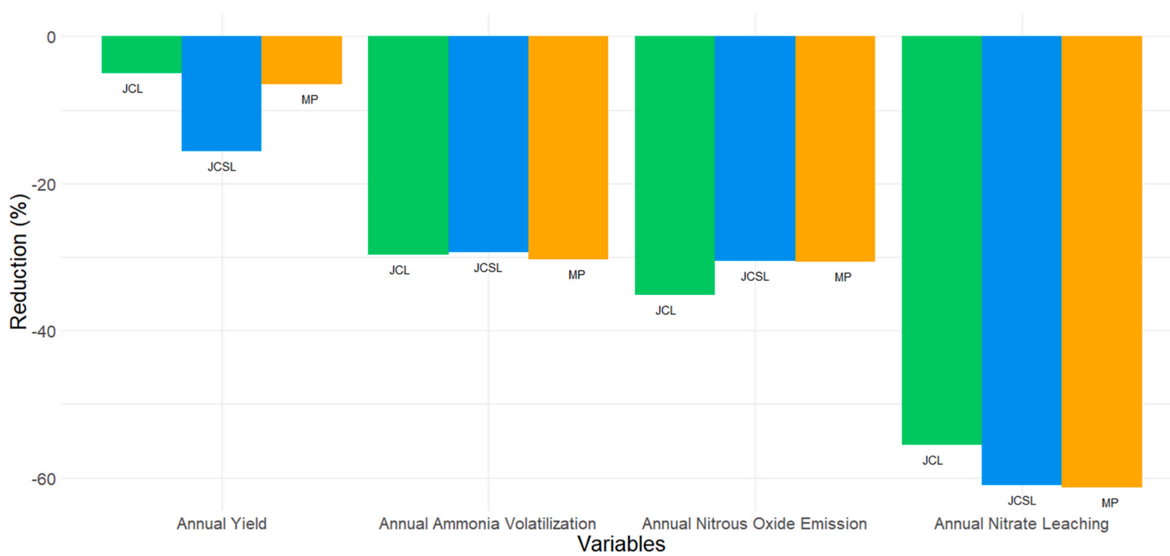

Fig. 3. The reduction (%) in annual yield of perennial ryegrass, annual ammonia NH_3) volatilisation, annual nitrous oxide (N_2O) emissions and nitrate (NO_3^-) leaching when N fertiliser input (urea) was reduced from GB Regime to NAP Regime.

content represented by soil texture at JCL. The study showed that higher annual NH_3 volatilisation was partially associated with lower annual rainfall and average annual temperature. The highest annual NO_3^- leaching under the GB regime was modelled for JCSL, followed my MP and JCL, whereas the highest annual NO_3^- leaching under the NAP regime was modelled for JCSL followed by JCL and MP. Under the GB regime, higher annual NO_3^- leaching was associated with higher SOC and lower - BD, WFPS at FC and WP and plant available water and lower annual NO_3^- leaching was partially associated with soil sand content. Whereas under the NAP regime, the lower annual NO_3^- leaching at MP site was partially associated with higher annual rainfall and higher average annual temperature.

With a reduction of annual N fertiliser input under the NAP regime, the reduction in the estimated annual yield varied from −4.98 % at JCL to −15.62 % at JCSL (Table 4; Fig. 3). The reduction in the estimated annual NH_3 volatilisation ranged from −29.40 % at JCSL to −30.35 % at MP (Table 4; Fig. 3). The reduction in the estimated annual N_2O emissions was from −30.49 % at JCSL to −35.15 % at JCL (Table 4; Fig. 3). Whereas for the estimation annual NO_3^- leaching, the reduction varied from −55.51 % at JCL to −61.38 % at MP (Table 4; Fig. 3).

With the reduction in annual N fertiliser application from the GB to the NAP regime, the reduction of annual yield was highest for JCSL followed by MP and JCL. Whereas the NAP regime resulted in the highest estimated reductions of annual NH_3 volatilisation at MP, followed by JCL and JCSL, whereas the highest reduction in annual N_2O emissions was at JCL followed by MP and JCSL. The reduction in annual NO_3^- leaching under the NAP regime was highest at MP followed by JCSL and JCL. The smaller reductions in yield estimates under the NAP regime at JCL was a site with a lower sand content. The reductions in yield were higher for sites with higher SOC and lower BD, WFPS at FC and WP and plant available water (derived from WFPS at FC and WP), including between the two sandy loam soils at JC and MP. The reduction in NH_3 volatilisation due to the reduction of N fertiliser input under the NAP regime (DAFM, 2023), greater for the MP site, was associated with higher annual rainfall and annual average daily temperature. Unlike annual yield and annual NH_3 volatilisation, the same factors that were responsible for higher annual N_2O emissions were also associated with the larger reduction in annual N_2O emissions under the NAP regime. The sites with a higher estimated annual N_2O emissions were also associated with a higher reduction in annual N_2O emissions. Whereas larger reductions in annual N_2O emissions, highest at JCL and lowest at JCSL, were aligned with lower SOC and higher BD at these sites. Under the NAP scenario, the model estimated that the reduction in NO_3^- leaching was higher for sites with relatively lower pH and clay. A larger reduction in NO_3^- leaching was partially associated with higher sand content, annual rainfall and temperature.

4. Discussion

4.1. Key drivers of yield variation across the three studied sites

Based on the findings, lower sand content and higher WFPS at FC and WP (the difference of which represent higher plant available water) resulting in higher water availability likely contributed to the increased yields (Anderson, 1988; Pragg et al., 2024). The observed association of lower SOC with higher yield could not be explained clearly, as lower SOM (soil organic matter), represented by lower SOC (Pribyl, 2010), generally has a negative impact on soil water-retention, nutrient supply, soil aggregate stability, buffering capacity against pH, BD and CEC (Blanco-Canqui and Benjamin, 2015; Djajadi et al., 2012; Libohova et al., 2018; Ramos et al., 2018; Robertson and Paul, 2000; Zhang et al., 2017). However, one potential explanation for the association between the relatively lower SOC and higher yield could be due to the decreased potential for seasonal waterlogging due to lower SOM. This is common in wetter months in Ireland and can particularly affect yield by increasing leaching and denitrification or by inhibiting respiration in roots leading to reduced water uptake (Hurtado-Uria et al., 2013; Jiao et al., 2004; Lehmann and Schroth, 2002; Smith et al., 2022; Yin et al., 2020), where SOC is not a limiting factor. A prolonged period of high soil moisture during winter months was also identified by Schulte et al. (2012) as a challenge for grass growth in Atlantic maritime conditions, including Ireland. The modelled year of 2019 at both of the studied farm locations were also ideal representatives of this general weather pattern of Ireland (Met Éireann, n.d.). This may also provide an explanation for the association between higher BD and higher estimated yields, as Fornara and Higgins (2022) showed that an increase in BD is associated with lower carbon content in soil.

The association between lower sand content and a smaller reduction in yield under the NAP regime may be associated with the relatively lower reduction of NO_3^- leaching under NAP regime observed in this site, indicating greater scope of its uptake (Novoa and Loomis, 1981). The same factors associated with higher yield are also associated with a lower reduction in yield under the NAP regime – which suggests that these factors are driving more efficient uptake of N by grass (e.g. Baligar et al., 2007; Orwin et al., 2015; Soares et al., 2019).

4.2. Key drivers of variation of ammonia (NH_3) volatilisation across the studied sites

Thompson et al. (1990) indicated that the impact of rainfall on NH_3 volatilisation is dependent on the timing of fertiliser applications and rainfall events. Thus, no direct conclusion on association between annual rainfall and NH_3 volatilisation could be inferred from the outcomes of this study. However, higher air temperature is generally associated with increases in NH_3 volatilisation (Huijsmans et al., 2001; Sommer et al., 2001), which is in contrast to the findings here. However, one possible explanation of the association between lower NH_3 volatilisation with higher rainfall and higher temperature is the dispersing effect of higher rainfall at MP on urea that prevents the accumulation of NH_3 and NH_4^+, overriding the effect of temperature (Harper et al., 1983). Higher rainfall may also contribute to increased downward movement of urea in the soil, thereby limiting NH_3 volatilisation (Bouwmeester et al., 1985). This indicates the relevance of employing weather forecast driven management for reducing NH_3 volatilisation (Hargrove, 1988), by choosing the *right timing* and *right product* (Fixen, 2020), especially for sites showing higher susceptibility to NH_3 volatilisation (Patil, 2009; Wu and Ma, 2015). This study could not find a direct association between NH_3 volatilisation and yield or N_2O emissions. Under the NAP regime, the variation of annual NH_3 volatilisation across the sites was the same as the variation of NO_3^- leaching. However, under the GB regime, the variation of annual NH_3 volatilisation could not be associated with the variation of NO_3^- leaching. Thus, the effect of other forms of N loss on NH_3 volatilisation could neither be ruled out nor could be identified as responsible factors.

Higher soil moisture, due to high rainfall (Feng and Liu, 2015), has previously been found to increase NH_3 volatilisation (Milchunas et al., 1988). Higher temperature also increases NH_3 volatilisation (Huijsmans et al., 2001; Sommer et al., 2001). Thus, a reduction in N fertiliser application, especially ammonium supplying fertilisers like urea (Harty et al., 2017) in sites with higher rainfall and higher temperature may show higher efficiency in reducing annual NH_3 volatilisation, which are also the sites that are relatively less vulnerable to loss of N through NH_3 volatilisation due to overriding effect of annual rainfall on average annual temperature, as was also seen in this study. However, unlike annual NH_3 volatilisation, higher rainfall overriding the effect of average annual temperature, cannot be identified as the only determinant for the reduction in NH_3 volatilisation under the NAP regime.

4.3. Variation of nitrous oxide (N_2O) emissions across the studied sites

WFPS is a key driver of N_2O emissions, potentially due to increased anaerobic conditions under increased WFPS, and ultimately governed by the interaction of soil water holding capacity and rainfall (e.g. Griffis et al., 2017; Liu et al., 2022; Newman, 1984; Yin et al., 2020; Zhang et al., 2021), that justifies the outcomes of this study. However, variation in rainfall did not explain the variation in annual N_2O emissions. Whereas the association of higher annual N_2O emissions with finer soil texture is justified as coarser soils generally show lesser anaerobic condition, which is a key driver of denitrification, due to reduced water retention and reduced N availability due to higher leaching (Newman, 1984; Saggar et al., 2013; Sahrawat, 2008; Wei et al., 2021). Lower SOC for sites with higher estimated annual N_2O emissions is counter intuitive with denitrification from SOC, typically associated with the availability of substrate carbon (Beauchamp et al., 1980). However, lower SOM, may reduce water retention leading to reduced denitrification (Rawls et al., 2003; Yin et al., 2020). The association of lower N_2O emissions estimated for sites with lower BD, that also might be associated with lower SOC in these sites (Fornara and Higgins, 2022), is likely driven by increased anaerobic conditions (Czyż, 2004). Sites with higher N_2O emissions were also those with higher potential yield, indicating similar factors that drive high yield may also drive high annual N_2O emissions - as was seen from this study. It also indicates that the surplus N after uptake by plant (Smith et al., 2012) is not the only determinant of N_2O emissions, under the site conditions and management intensity used in this study.

This study indicates that the sites that are more vulnerable to N_2O emissions may respond more efficiently to a reduction in N supply in terms of N loss through N_2O emissions. This is possibly due to the effect of higher annual yield coupled with a smaller reduction in annual yield leading to improved NUE in these sites with higher WFPS at FC and WP and plant available water. This suggests lower availability of substrate N for denitrification, further reduced by relatively lower availability of substrate carbon, overriding the intrinsic vulnerability of the site to potential higher denitrification (i.e. higher anaerobic conditions driven by higher BD and finer texture) (Anderson, 1988; Beauchamp et al., 1980; Czyż, 2004; Pragg et al., 2024; Rawls et al., 2003; Ritchie, 2021; Soares et al., 2019; Wei et al., 2021; Yin et al., 2020).

4.4. Variation of nitrate (NO_3^-) leaching across the studied sites

The variation of annual NO_3^- leaching across the sites was not same for the GB regime and NAP regime. Thus, it was not possible to identify factors in common with annual NO_3^- leaching. However, this also indicates that depending on the rate of N fertiliser application the susceptibility of a site to annual NO_3^- leaching and its key drivers can vary. Hence policy-specific spatial refinement for reducing annual NO_3^- leaching may be required (Patil, 2009; Sharma and Bali, 2017; Wu and Ma, 2015). Lower annual NO_3^- leaching being partially associated with lower sand content in the soil under GB regime is consistent with more general observations (e.g. Anderson, 1988; Wei et al., 2021). The association between the higher WFPS at FC and lower annual NO_3^- leaching under GB regime is justified as higher field capacity would require a higher amount of water for saturation and the consecutive initiation of leaching (Wang et al., 2019). Whereas the association between higher plant available water, derived as the difference between WFPS at FC and WP (Pragg et al., 2024) and that was also associated with higher yield, with lower annual NO_3^- leaching under GB regime indicates reduced availability of NO_3^- leaching due to greater uptake (Novoa and Loomis, 1981). Higher SOM, indicated by higher SOC (Pribyl, 2010), may reduce the annual NO_3^- leaching due to improved water retention (Whetton et al., 2022), and can explain the variation of annual NO_3^- leaching under GB regime in our study. Sites with higher BD, indicating lower porosity that reduces rate of infiltration, likely explains the lower estimated annual NO_3^- leaching under GB regime (Panagos et al., 2022). Increased NO_3^- leaching under higher temperature was found by Jabloun et al. (2015) and is in contrast to the findings in this study for NAP regime. Whereas higher rainfall associated with lower annual NO_3^- leaching seen under NAP regime is likely driven by variations in cumulative rainfall over different seasons (Jabloun et al., 2015) or the intensity of rainfall (Sugita and Nakane, 2007). Thus, future research could consider whether the distribution of seasonal rainfall and/or intensity of rainfall produces an overriding of the effect of annual rainfall and average temperatures in Irish grasslands.

Increased soil acidity can lead to reduced nitrification and a subsequent increased accumulation of NH_4^+ (Kemmitt et al., 2005), while higher clay content generally contributes to a reduction in N leaching due to higher water retention (Wei et al., 2021; Whetton et al., 2022). This, when coupled with reduced nitrogen supply, may accelerate the reduction of NO_3^- leaching as was seen in this study under NAP regime. This indicates that sites with higher sand content and/or annual rainfall and temperature that are more susceptible to N leaching (e.g. Anderson, 1988; Wei et al., 2021; Jabloun et al., 2015; Sugita and Nakane, 2007) may have greater efficiency in reducing NO_3^- leaching under a reduced rate of fertiliser application.

4.5. Significance for geographically refined national policies for sustainable nitrogen (N) management

The study shows that a uniform reduction of N fertilisers nationally, for a fixed stocking rate, may not meet the targeted yield for farms under the diverse range of environmental and meteorological conditions experienced. Such a uniform reduction may be unable to effectively reduce surplus N across spatially diverse sites, which ultimately governs the variation of N loss in different forms (Wu and Ma, 2015). Thus, determining the adequate N fertiliser requirement at farm or field level may help inform the *right rate* of N fertiliser application, as per the 4RNS objectives (Fixen, 2020) to achieve a targeted yield and a reduction in N loss. The geographical refinement of national level strategies can be achieved by developing national management zones leading to more focused N management practices based on potential yield and N loss (Patil, 2009; Wu and Ma, 2015). The outcomes of this study indicate such geographical refinement of the existing national sustainable N management strategies in Ireland could be achieved by developing management zones. However, the effectiveness of the policy implementation under diverse soil and meteorological conditions can vary, which will be relevant for upscaling or downscaling of management strategies (Milne et al., 2020; Patil, 2009).

To support the implementation of improved, geographically refined, N management strategies, we hereafter classified the key regulators of variability of yield, N loss and their changes across the study sites under a uniform reduction of N fertiliser application, identified from this study, into two groups. Group 1 consists of the variables that explained the variation of N loss across the studied sites and can be used as proxy or indicator variables for estimating potential yield, NH_3 volatilisation and N_2O emissions, which could help in the development of N management zones nationally (Nabati et al., 2020; Patil, 2009). The variables that explained the absolute reduction in yield and N loss through NH_3 volatilisation and N_2O emissions, as well as through NO_3^- leaching, under the NAP regime, were grouped in a second group (Group 2) as effective regulators to achieve targeted sustainability objectives to improve or maintain productivity and the reduction of N loss to support further refinement of strategies policy implementation at a higher spatial and temporal resolution within the management zones (Schipanski et al., 2009; Shirmohammadi et al., 2008).

4.5.1. Group 1 variables

It was observed that high yielding sites can act as potential indicators of high annual N_2O emissions – thus can lead to formation of national to field level management zones for the spatial refinement of N management plans that aim to achieve a targeted yield while reducing N_2O emissions from grassland soils (Nabati et al., 2020; Patil, 2009). Sand content in soil emerged as an independent but common regulator for yield and N_2O emissions, that may be suitable for developing time independent mapping of management zones using data at a national scale (e.g. O'Sullivan et al., 2018) for refining national level N management strategies (e.g. Milne et al., 2020; Patil, 2009). Although BD and SOC were identified to be indicators of annual yield and N_2O emissions, their potential impact on N dynamics driven by their interaction with the environment and each other (e.g. Czyż, 2004; Fornara and Higgins, 2022; Hurtado-Uria et al., 2013; Jiao et al., 2004; Lehmann and Schroth, 2002; Smith et al., 2022; Yin et al., 2020), may make them unsuitable for developing management zones as individual variables. However, national spatial data on soil BD (e.g. O'Sullivan et al., 2018) and SOC can be useful in combination to develop management zones (Patil, 2009), which together with textural zones may increase the spatial resolution of refinement of N management strategies. Although BD and SOC can vary depending on management practices, consistent land use practice over a long period (decades) can stabilise these factors (e.g. Bauer and Black, 1981; Evans et al., 2012). This makes historical land use an important factor to consider if using BD and SOC for developing management zones. However, WFPS at FC and WP, and thus the plant available water (Pragg et al., 2024), can be subject to change due to management activities like organic matter additions (Minasny and McBratney, 2017). Hence, while they may initially indicate the potential of yield and N_2O emissions they may not be suitable for use in developing management zones.

Climate data, over long time periods (e.g. 30 years) (e.g. Walsh, 2012), on annual average rainfall and temperature is relevant for identifying management zones (Patil, 2009) to reduce potential NH_3 volatilisation, as higher NH_3 volatilisation was seen to be associated with lower annual rainfall and lower average annual temperature. Such zones can be compared with national level monitored data on NH_3 volatilisation for further refinement (e.g. Doyle et al., 2017). However, as long-term climate averages may fail to represent annual variations in weather (Krishnamurthy, 2019), to reduce NH_3 volatilisation there would still be a need to monitor and model the potential impact of a management plan and to adapt decision making to incorporate weather forecast information (Burchill et al., 2016; McDonnell et al., 2019).

It was seen from this study that, unlike for yield and N loss through NH_3 volatilisation and N_2O emissions, the suite of environmental regulators that explain the variation of annual NO_3^- leaching across sites can vary depending on the rate of N fertiliser application. For example, we found that the factors that explain the high to low variation in annual NO_3^- leaching across the studied sites under the GB regime were consistent with the factors relevant for explaining low to high variations in annual yield and annual N_2O emissions. Whereas under the NAP regime, the factors that explained the high to low variation in annual NO_3^- leaching were the same factors that explained the high to low variation in NH_3 volatilisation. The variation in annual NO_3^- leaching under GB regime were not associated with the variation of annual NH_3 volatilisation while under NAP regime this variation was not associated with the variation of annual yield and annual N_2O emissions. Thus, for annual NO_3^- leaching, developing time-independent management zones would not be a suitable option, unless the N application rate is consistent. Rather, the effect of a management regime on annual NO_3^- leaching across sites can be determined through further modelling or monitoring (EPC, 1991) along with identifying the relative importance of the regulatory factors under that regime, that might help in determining management zones (Patil, 2009) under a specific regime.

4.5.2. Group 2 variables

This study also showed that the impact of changes in N management plans in a spatially uniform manner varies, depending upon soil and weather conditions. Thus, it is important to consider the potential effectiveness of any current or potential future policies and their regulators (Schipanski et al., 2009; Shirmohammadi et al., 2008). Despite the varying relevance of regulatory environmental factors on annual NO_3^- leaching under the GB and the NAP regime (see section 1.4.4 for more details), soil clay content and pH explained the reduction in annual NO_3^- leaching under the NAP regime. Whereas soil sand content, as a common factor, partially explained the reduction in annual N_2O emissions, annual NO_3^- leaching and the reduction of yield under the NAP regime. BD and SOC, initial WFPS at FC and WP and plant available water are also found to be associated with the efficacy of the implemented management regimes to reduce N_2O emissions and achieve sustainability in maintaining yield. Thus, soil textural properties, BD, SOC, pH, WFPS at FC and WP and plant available water are important to account for when developing sustainable N management plans. However, since soil texture, BD and SOM (represented by SOC) ultimately govern the water holding capacity of soil (Carter, 2002; Pribyl, 2010), accounting for these variables may reduce the need to account for WFPS at FC and WP and plant available water. The identified variables have potential to inform N management strategies at a higher resolution and could be useful to develop sub-divisions of management zones (Milne et al., 2020; Patil, 2009; Shirmohammadi et al., 2008). Importantly, they can be used to analyse the potential outcomes of future national level strategies at more localised scales, by exposing vulnerability to loss pathways. Further, monitoring annual yield, NH_3 volatilisation, N_2O emissions and NO_3^- leaching at a higher spatial and temporal resolution, depending on estimated vulnerabilities to inefficient N uptake or reduction of loss, is critical for improving the effectiveness of any implemented policy on reducing N loss, choosing the best among the alternatives and to spatially optimise N management plans (Doyle et al., 2017; EPA, 2023a; EPC, 1991; IPCC, 2000; O'Donovan et al., 2021; Patil, 2009). This can be important to inform and evaluate the success or failure of potential or implemented strategies within designated sub-divisions of management zones and to identify requirement or scope of empirical studies to further refine N management strategies – such as choosing right product and right timing (Fixen, 2020) for N fertiliser application. Annual rainfall and average annual temperature were identified to explain the efficiency of NAP in reducing both NH_3 volatilisation and NO_3^- leaching, making weather forecast relevant for decision making on N application with respect to timing, location and type (Fixen, 2020; McDonnell et al., 2019).

4.6. Scope for refinement of site-specific N management – future application potential

Our study indicates that spatially refining N management plans is relevant for sustainable grass yield and achieving a targeted reduction of N loss over uniform national level N management plans, to address the productivity challenge. This research highlights the scope for the spatial refinement of national policy and farm level advice that can be tailored to zones in line with the *right place* objective of the 4RNS strategy (Fixen, 2020) and can be further refined by understanding the potential impact of implemented policies on yield and N loss at a higher spatial resolution (e.g. Milne et al., 2020; Patil, 2009; Shirmohammadi et al., 2008).

We suggest that zoning for Irish landscapes can be employed for refinement of N management focusing on zones based on susceptibility to - NH_3 volatilisation (*V* Zone), high denitrification (*DN* Zone) and high nitrate leaching (*L* Zone), categorised with prefix '*h*' for 'high' and '*l*' for 'low' vulnerability in each case. For zones susceptible to high NH_3 volatilisation (*hV* Zone), application of urease inhibitors for urea application and the use of more nitrate-based fertilisers instead of ammonium-based fertilisers should be encouraged to reduce NH_3 volatilisation loss, according to the *right source* objective of 4RNS strategy (Fixen, 2020; Forrestal et al., 2015; Harty et al., 2017). For zones susceptible to high denitrification (*hDN* Zone) and nitrate leaching (*hL* Zone), the application of nitrification inhibitors and the replacement of nitrate-based fertilisers with more ammonium-based fertilisers can be suggested to meet the same objectives (Rahman and Forrestal, 2021; Woodward et al., 2021). At the same time, choosing the *right time* for N fertiliser application, based on weather forecast, at the *right place* can also be supported through such zoning to achieve 4RNS goals (Fixen, 2020; McDonnell et al., 2019). Application of urea or ammonium-based N fertiliser application should be postponed from a tentative application date days if rainfall has occurred or forecasted on the day before the tentative date and with a forecast of low rainfall on that date and subsequent days, especially in *hV* Zones (Hargrove, 1988). For *hDN* Zones, the application of N fertiliser should be avoided on days immediately after rainfall events or when rainfall is forecasted to occur after the N fertiliser application (Craswell, 1978; Schwenke and Haigh, 2016). Sub-division of existing management zones for yield and other forms of N loss into *hL* Zones, using the variables that were identified regulating the variation of reduction of NO_3^- leaching under NAP regime (Group 2), can help in implementation of GAP (EPC, 1991) to reduce pollution from NO_3^- leaching. Whereas *hL* Zones can also be identified based on regulators of annual NO_3^- leaching under each specific management regime, with the same objectives, depending on duration of the management regime. To reduce potential NO_3^- leaching, nitrate-based fertiliser application should be avoided on days forecasted with high intensity rainfall (Di and Cameron, 2002; Hess et al., 2020), especially relevant for *hL* Zones.

Though such options of zoning may support decision making processes and modifications of policies according to the specific requirements of particular locations, a challenge for such zoning would be availability of data to develop zones and understand if such zones represent field conditions of N loss. In the case of Ireland, one applicable method is clustering (Carlier et al., 2021) based on soil data collected nationally (e.g. O'Sullivan et al., 2018), in combination with long term climate data (Curley et al., 2023). However, data for validation of such zones to find, whether or not they are representing the susceptibility of the landscape to specific type of N loss, might require higher resolution data on N loss from field conditions from study sites across the nation under uniform management for comparison - unlike the datasets that represent more general national distribution of atmospheric concentration of emitted gases or nitrate in water (e.g. Doyle et al. 2017; EPA, 2023a), that are ultimately governed by several environmental factors that might not be directly or indirectly related to agricultural N management. A useful strategy for such data collection can be knowing the upper and lower limits of specific soil properties and climate conditions of the clusters, selecting representative sites and performing nationwide field experiments under different spatially uniform N application regimes and determining the reliability of the clusters to represent the spatial variation of N loss, with identifying the zones that represent N loss beyond expected limits under each management regime for designating as high N loss zones (e.g. *h*V, *h*DN, *h*L). If such experiments for data collection are not feasible, the DNDC model can here be employed for each intensive management regime (Abdalla et al., 2009) for the sites, selected after clustering, representing upper and lower limits of the cluster.

5. Conclusion

This study primarily sought to identify the possible scope of geographical refinement of national level sustainable N management strategies for dairy farming to improve agricultural productivity and to reduce N loss to the environment from grasslands under Irish dairy farming. The DNDC model, that had been parameterised to reliably estimate the annual yield of perennial ryegrass following existing literature, was used to estimate the impact of two national level intensive N management strategies, that are currently spatially uniform, on grass yield and N loss, with site-specific soil inputs required for reliable estimation of NH_3 volatilisation and N_2O emissions. The outcomes showed that there is potential to improve strategies that reduce N loss through NH_3 volatilisation, N_2O emissions and NO_3^- leaching, if N management strategies can be geographically refined, considering the key regulators that spatially modify these outcomes. To maintain a targeted yield sustainably, such geographical refinement was found to be a requirement. The study showed that the variability of perennial ryegrass yield and different forms of N loss through NH_3 volatilisation and N_2O emissions, seen across the studied sites, are dependent on each other (except for NH_3 volatilisation under GB regime), as well as on the diversity of the soil texture, pH, BD, SOC, plant available soil water and on average annual temperature and annual rainfall. It was also evident that combinations of such variables become important for regulating the effectiveness of an implemented N management strategy to maintain yield and reduce N loss. Whereas identification of key regulators of NO_3^- leaching needs to be performed for each uniform management regime for similar purpose. The Group 1 variables, that indicate potential yield and N loss, may be used to develop national level to farm level management zones for geographical refinement of existing aspatial N management strategies, depending on their temporal stability, to determine timing, rate and form of N fertiliser application, depending on the requirement to meet the targeted yield and the susceptibility of the site located in a specific zone to specific forms of N loss. Furthermore, accountability of the identified factors in this research that influence the effectiveness of N management strategies (Group 2 variables) offer scope to assess and analyse the impact of policies with respect to meeting both production and environmental targets in line with national ambitions, by knowing the potential effectivity of N management strategies based on the indicators of efficiency.

CRediT authorship contribution statement

Sudipto Bhowmik: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rowan Fealy:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **David Wall:** Writing – review & editing, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Réamonn M. Fealy:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Lilian O'Sullivan:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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