The Impact of Nitrogen Management Strategies within Grass Based Dairy Systems

The Impact of Nitrogen Management Strategies within Grass Based Dairy Systems

Prepared by:
Laurence Shalloo, Elodie Ruelle, Karl Richards, Daniel Hawtree, Donal O Brien, David Wall, Michael O'Donovan, Deirdre Hennessy and Pat Dillon

Teagasc, Oak Park, Carlow, Ireland

February 2023 ***ISBN:*** *978-1-84170-688-7*

Contents

Executive Summary

- The Irish agriculture landscape is heterogeneous where both static (e.g. soil and bedrock type, thickness and permeability) and dynamic factors (e.g. climate, soil moisture deficit, water table depth) influence N leaching. There is a variable hydrologic and biogeochemical time lag (months to decades) between N surplus losses and changes to water quality and this must always be acknowledged when considering the efficacy of programmes of measures. The connection between source loading and N export rates will also be impacted by inherent temporal lags in catchment response. Expected water quality improvement as a result of mitigation measures may be delayed for groundwater pathways due to variable drainage amounts and delayed responses of nitrate in deep aquifers. In meso-scale catchments, a positive response occurred from 1-10 years after decreased N surpluses were achieved, with the response time broadly increasing with catchment size.

- The Irish Agricultural Catchment Programme (ACP) has shown that nitrate-N concentrations in groundwater and streams are primarily controlled by catchment physical characteristics (e.g., soil hydrogeological factors), meteorological conditions, and agronomic practices. Stocking rate, in and of itself, was not found to be a primary driver of nitrate-N concentrations in most cases. For example, over the period 2010 to 2017 a significant increasing temporal trend in ground water nitrate-N concentration was observed in a tillage catchment (Castledockerell) with vulnerable soil hydrogeological characteristics. By contrast, in an intensive grassland catchment (Timoleague), no long-term trend was observed, despite the proportion of land area in derogation increasing as well as overall organic loading (stocking rate) increasing from 134 kg N /ha in 2008 to 182 kg N/ha in 2018. In recent years there is indications that nitrate-N concentration are reducing in the Timoleague catchment.

- Elevated nitrate-N concentrations were observed in most ACP catchments in 2018/19, which was driven by a nation-wide drought in 2018 resulting in a build-up of a large soil N pool and enhanced soil N mineralisation. This was compounded by increased use of artificial N, extended spreading until mid-October and increased purchased feed. Since 2018, based on this experience, improved fertiliser application guidelines have been issued to farmers during and after dry summer conditions to reduce N losses on farms. For example in 2022 during a period of reduced grass growth the advice was to reduce chemical N application (Table 3)

- The 5th Nitrate Action Programme has introduced a significant number of new actions designed to reduce nutrient loss in order to improve water quality. In March 2022, the closed period for both slurry spreading and chemical N fertilizer application was increased and the maximum chemical N fertilizer rates were reduced. From 2022, new soiled water storage requirements were introduced, further reductions in the maximum chemical N application rates are possible in 2024; the introduction of an N fertilizer register will occur in 2023 and the introduction of N excretion banding for dairy cows will happen in 2023. Additionally, the recent published Food Vision Dairy and Beef & Sheep reports recommend further significant reductions in fertiliser N application rates. These are far-reaching changes that will require time to be implemented and time for the impact on water quality to be evaluated.

- Two separate modelling approaches were used in order to increase the confidence of the model outputs. The MoSt GG/PBHDM is a dynamic mechanistic model that simulates a range of physical characteristics with a daily time step while the €riN model is a budgetary simulation model operating at a monthly time step. While both approaches generated N outputs and losses the MoSt GG/PBHDM modelling approach specialized on the impact of weather, chemical N and organic N/ha on grass growth, farm feed budget and N use efficiency. The €riN model specialized on the impact of chemical N and organic N/ha on N use efficiency and gaseous N emissions. In the analysis it was assumed that the soil type was free draining and therefore this analysis shows the worst case scenario.

- The predicted impact of reduced chemical N on N leaching was similar for both modelling approaches (MoSt GG/ PBHDM and €riN). Using the MoSt GG model, reducing chemical N, at an organic N level of 250 kg of N/ha, from 250 kg/ha to 225 kg/ha, (10% reduction), 200 kg/ha (20% reduction) and 175 kg/ha (30% reduction) resulted in a reduction of N leaching to 1m by 1.3 kg/ha (2.1%), 2.7 kg/ha (4.4%) and 3.9 kg/ha (6.4%) respectively. The corresponding N leaching reductions using the €riN model were 2, 4 and 6 kg/ha, respectively. Using the €riN model a reduction in chemical N fertilization from 250 to 175 kg N/ha resulted in a reduction in gaseous ammonia, dinitrogen and nitrous oxide emission by approximately 1 kg, 3 kg and 1 kg/ha, respectively. Reducing chemical N application rates (kg N/ha) from 250 to 225, 200 and 175 reduced grass production (kg DM/ha) by 360, 736 and 1,133 kg, respectively. The corresponding reduction in profitability (€/ha) were €116, €224 and €322, respectively.

- The impact of reduced chemical N application on grass production and profitability can be somewhat offset at farm level by greater use of low emission slurry spreading technology, increased soil fertility (including soil pH), greater precision in the use of chemical N application on grassland and incorporating white clover into swards. For example, previous research has shown that low emissions slurry spreading and timing will reduce chemical N requirements and that increasing soil fertility from suboptimum to optimum will reduce chemical N requirement by 50 – 70 kg N/ha. A perennial ryegrass white clover pasture has the potential to fix between 80 – 140 kg of N per hectare annually. Use of precision chemical N application to grassland has the potential to increase responses from chemical N while at the same time reduce leaching losses.

- Similar to the reduction in chemical N, both modelling approaches (MoSt GG/ PBHMN and €riN) produced similar impact of a reduction of organic N/ha (stocking rate) on nitrogen leaching. Using the MoSt GG model, reducing organic N/ha from 250 kg to 230 kg (8% reduction) and 250 to 220kg (12% reduction), at a chemical N application of 250 kg N/ha, was estimated to reduce N leaching by 1.5 kg/ha (2.5%) and 2.2 kg/ha (3.6%) respectively at one meter depth. The corresponding reductions using the €riN model were 3 and 4 kg/ha, respectively. A reduction in organic N from 250 to 220 kg/ha resulted in a reduction in gaseous ammonia, dinitrogen and nitrous oxide emission by approximately 11 kg, 5 kg and 1 kg/ha, respectively. Reducing organic N/ha from 250 to 230 and 250 to 220 reduced farm profitability per ha by €246 and €374/ha respectively. These reductions in profitability/ha highlight the importance of grass utilization in pasture based system. Reducing organic N from 250kg/ha to 220kg/ha had three times greater impact in reducing profitability/ha than reducing chemical nitrogen by 10%.

- DAFM, introduced three new livestock excretion banding rates related to milk yield/cow for dairy cows from 1st of January 2023 as part of the Nitrates Action Programme. These included a 80 kg N/cow (<4,500 kg milk/cow), 92 kg N/cow (4,501 to 6,500 kg milk/cow) and 106 kg N/cow (>6,501 kg milk/cow). In the organic N excretion Band 1 category (80 kg N/cow) both the proportion of milk produced and proportion of milk suppliers reduced over the period 2015 to 2021 from 15% to 6% and from 25% to 15%, respectively. In contrast, in the organic N excretion Band 3 category (106 kg N/cow) both the proportion of milk produced and milk suppliers increased over the period 2015 to 2021 from 13% to 26% and from 9% to 19% respectively.

- In the context of farms who are above the maximum 250 kg organic N/ha as a consequence of the introduction of banding, the least negative financial strategy at farm level to reduce organic N would be to contract rear or rear less replacement heifers or rent additional land. Exporting slurry is not practical given the quantities that are to be exported and its impact on soil fertility of the exporting farm as most grassland are close to farm P balance and therefore exporting will create a deficit across the overall farm. In the analysis shown, reducing cow numbers from optimal has the most significant negative impact on farm profitability. It is therefore likely that farmers will attempt to exhaust other available options before a reduction in herd size is considered. While some dairy farms will find it very difficult to adjust their farming system to the new organic N excretion banding at a maximum organic N/ha 250, reducing the maximum organic N/ha to 220 would cause significantly greater difficulties for these farms. From the analysis and scenarios completed in this report the combined effect of banding and reducing from 250 to 220 could reduce profitability by 29% in the most extreme scenarios.

- The analysis carried out in this report suggest that current changes that are being introduced in the 5th Nitrate Action Programme coupled with increased ambition in fertiliser N reductions in the Food Vision strategy, would result in a reduction in N leaching of between 5.9 kg/ha MoSt GG and circa 9kg/ha from the €riN model. Reducing organic N/ha from 250 to 220 kg N/ha will only reduce N leaching by an additional 2.2 kg N/ha using the MoSt GG model (circa 4 kg €riN), but it will have a significant financial impact at farm level. Consequently, in order to optimise the cost : benefit ratio, a sequential approach to firstly allowing the impact of the 5th NAP and the additional fertiliser reductions in the Food Vision Dairy Group Report to be assessed before introducing any reduction in organic N limits would be desirable. Additionally, the reductions in N leaching should go a long way in meeting the N reductions required at a catchment level identified by the EPA (WFD River Basin Management Plan – 3rd Cycle), to achieve a water quality standard of 2.6 mg N/l in the downstream estuary.

- The competitive advantage of grass-based systems are based on maximising grass utilisation. Where stocking rate is not sufficient relative to pasture growth potential on a farm, it will result in lower grass utilisation, lower sward quality and reduced animal performance. On well-managed productive grassland farms in Ireland, reducing organic N/ha from 250 to 220 will result in significantly reduced farm profitability. Research work conducted both in Ireland and internationally, has shown that increasing stocking rates while both chemical N fertilizer per hectare and concentrate input per cow are held constant (static N), results in stable or declining nitrate leaching compared to lower stocking rates due to the higher grass utilisation and greater export of N in milk. The imposition of a lower organic N limit per ha could also move farmers away from pasture based systems to a higher input system (more bought in feed) in an attempt to maintain milk output from the farm. The lower organic N limit may also result in more uneven distribution of organic nutrients within farms. International experience has shown that high input systems pose a higher risk to the environment and these organic N policy changes may increase the likelihood of that happening. Additionally, derogation farms (greater than 170 kg of organic N/ha) are required to implement a higher standard of nutrient management than non-derogated farms (less than 170 kg of organic N/ha) in terms of nutrient management, soil testing, manure and slurry spreading, grassland management and training.

Background

The Department of Agricultural, Food and Marine (DAFM) requested Teagasc to simulate the impact (environmental and economic) of a number of farm nitrogen (N) mitigation measures in order to inform policy of the best current and potential actions to deliver the catchment-based nitrate load reduction estimated by the EPA in 2021. That resulted in a report published in July 2021 (https://www.teagasc.ie/media/website/publications/2021/Nitrates-Modelling-Final.pdf). In July 2022, DAFM requested Teagasc to undertake further analysis. The following were requested to be investigated:

1. A review of the literature on the impact of land use, farming system, stocking rate, nitrate regulations on water quality on grass based systems in Ireland.
2. Trends in water quality from the Agricultural Catchment Programme.
3. Reduction in chemical N fertilizer application of approximately 10%, 20% and 30%, i.e. chemical N application rates of 250, 225, 200 and 175 kg/ha.
4. Stocking rate reduction - 250 kg N/ha (2.74 cows/ha), 230 kg N/ha (2.50 cows/ha) versus 220 kg N/ha (2.39 cows/ha).
5. Proportion of farms and milk that were in each of the different bands from 2020 and 2021.
6. Economic consequences of banding if associated with a reduced stocking rate at farm level.

1. A review of the literature on the impact of land use, farming system, stocking rate, nitrate regulations on water quality on grass based systems in Ireland

1.1. Land use

Data from Eurostat show that Ireland had by far the highest percentage of utilized agricultural area under grassland in 2016 at 90.4%; the next highest is Slovenia at 58.4% (Figure 1). Overall in Ireland, 67% of the land area is farmed extensively, 33% is farmed under agro-environmental programmes and only 14% is farmed intensively. Pasture-based systems confer environmental advantages in terms of manure recycling, soil organic carbon content, forage self-sufficiency (including protein), greenhouse gas emissions per kilogram of product, and landscape diversity.

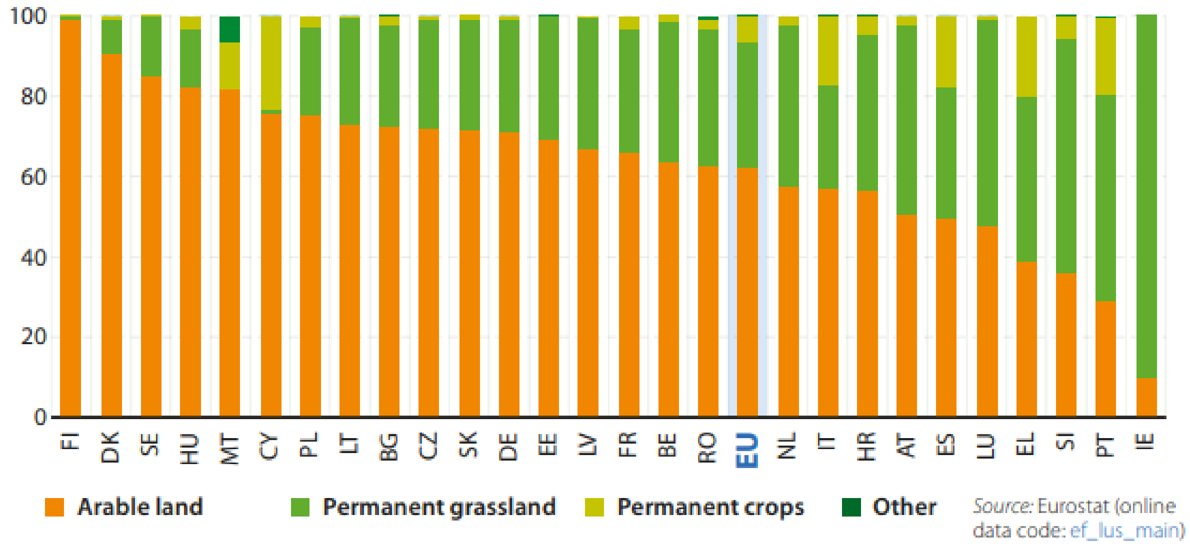


Figure 1. The utilisation of agricultural land in EU member states 2016 (Eurostat, 2017)

Irish grass-based systems of milk and meat production rely on the conversion of human inedible forage into highly nutritious and digestible human-edible products. O'Brien *et al.* (2018) reported that the average diet of dairy cows in Ireland was 81.8% forage, with concentrates constituting 18.2% of the annual feed budget on a dry matter basis. Of the 81.8% forage, 60.2% was grazed pasture, 19.8% was grass silage, and 1.8% was alternative forages. This is significantly different to farming systems in most other EU countries where grazed grass and grass silage constitute a smaller proportion of the cow's diet.

Reducing the maximum stocking rate from 250 kg N/ha to 220 kg N/ha for Ireland's nitrates derogation on top of the previous stocking rate reduction due to banding, could result in farmers altering their system to move away from grassland based milk production systems toward more cropping and conserved forage systems, in an attempt to achieve higher milk production per cow. This could have a negative impact from both a climate change and water quality perspective. The Irish Agricultural Catchment Programme (ACP) is in place since 2008 and is used to evaluate the impact of Ireland's Nitrates Action Programme and the Nitrates Derogation on water quality which are implemented under the Nitrates Directive. The programme is a collaboration with over 300 farmers in six river catchments to represent agricultural land with different levels of risk associated with N and P losses which are operated under differing enterprises.

The ACP has highlighted the importance of agronomic, meteorological and hydrology/hydrogeological factors in controlling N and P losses to water, which can override the impact of nutrient input intensity (i.e. stocking rate). For example, the ACP study catchment of Timoleague is dominated by pasture based dairy systems, and has the most land in derogation (66% in 2018) of all the ACP catchments. Despite an increase in the organic loading (stocking rate) in this catchment from 134 to 182 kg N/ha in 2008 to 2018, there was no statistically significant temporal trend in the ground water nitrate-N concentration during the 2010 to 2017 period (McAleer *et al.,* 2022). In contrast, the Castledockerell catchment, which is dominated by spring barley and has a low annual organic N loading (stocking rate), showed a minor increase from 35 to 45 kg N/ha from 2008 to 2018. There was a higher groundwater nitrate-N concentration compared to Timoleague, with a rising trend during 2010-2017 (McAleer *et al.,* 2022). Similar impacts have also been reported more recently by Dillon *et al.* (2021) when evaluating the impact of N management on N loss pathways.

The impact of meteorological and agronomic factors on N export is highlighted by the elevated observed nitrate-N concentrations in waterbodies during late 2018 and early 2019 (Mellander and Jordan, 2021). This was driven by a nation-wide drought which resulted in a build-up of a large soil N pool due to poor grass growth and enhanced soil N mineralisation. The effect was compounded by increased use of chemical N in late summer and autumn, as well as increased purchased feed. Subsequent analysis showed that the impact of the drought in 2018 on elevated nitrate-N concentration in surface and ground water could have been mitigated by operating a more precise and flexible N fertiliser management regime at farm level, when grass growth rates were significantly below normal (Dillon *et al.,* 2021). Since 2018, improved fertiliser application guidelines have been issued widely to farmers to reduce N losses from farms directly after periods of dry summer conditions. Based on analysis carried out on the implementation of precision fertilizer application strategies (especially in 2018) will have a much greater impact on improving water quality than reducing the maximum stocking rate from 250 kg N/ha to 220 kg N/ha for Ireland's nitrates derogation farmers. Furthermore, when considering inter-annual trends in water quality, year-to-year variability is not sufficient to assess the validity of any observed changes, and a longer time period is required (e.g., a minimum of four years would be required for statistical trends testing).

1.2. Impact of reducing stocking rate on N leaching (or organic N/ha)

Stocking rate is a key farm-level efficiency factor in successful grazing systems which facilitates the achievement of high levels of grazed pasture utilisation and milk production per hectare on dairy farms (McCarthy *et al.,* 2011, 2012). In defining the optimum stocking rate for resilient, pasture-based grazing systems, pasture utilisation is the principle considerations driven by good soil fertility, productive swards of perennial ryegrass and white clover. In Table 1, the optimum stocking rate (driven by grass utilisation) is defined for farms that produce different amounts of pasture and feed different amounts of supplement.

Table 1. Stocking rate that optimises profit on farms growing different amounts of pasture grown and feeding different amounts of supplement/cow

	Pasture grown, t DM/ha				
Supplement fed/ha, t DM	**12**	**14**	**16**	**18**	**20**
0.00	1.9	2.2	2.6	2.9	3.2
0.25	2.0	2.3	2.7	3.0	3.3
0.50	2.1	2.4	2.8	3.1	3.5
1.00	2.3	2.6	3.0	3.4	3.8
1.50	2.5	2.9	3.3	3.7	4.1

Although the beneficial impacts of optimizing stocking rate on grazing system productivity have been widely reported, the impact of stocking rate on environmental efficiency must also be considered.

Previous studies have indicated that where increased stocking rate is associated with increased chemical N fertiliser and supplementary feed importation, nutrient-use efficiency is reduced, nitrogen surplus is increased, resulting in increased N available to be lost to ground water and the general environment (Di and Cameron 2002; Treacy *et al.,* 2008; Ryan *et al.,* 2011). Contrary to these findings however, both McCarthy *et al.* (2015) and Roche *et al.* (2016) investigated the direct effect of stocking rate on nitrate leaching. Both studies reported either a stable or declining nitrate leaching with increasing stocking rate; the critical proviso, however, was that strictly no additional N fertiliser or supplements were introduced at higher stocking rate. On the basis of improved management practices, it is not correct to assume that N loss/ha through leaching increases as grass utilisation increases through increased stocking rate. Huebsch *et al.* (2013) showed that the nitrate-N concentration in groundwater in a free draining soil in Ireland declined over 11 years, despite a 20% increase in stocking rate. The reduced N leaching was associated with changes in management practices that included reduced chemical N fertilizer usage, improvements in timing of slurry application, increased precision grazing management, the movement of a dairy soiled water irrigator to areas deemed less vulnerable to leaching, and the use of minimum cultivation at reseeding. While Richards *et al.,* (2015) showed a reduced N surplus through reduced stocking rates and fertiliser levels in beef systems was associated with reduced N loss with the reduced N surplus component similar to the McCarthy and Roche studies.

1.3. Fifth Nitrate Action Programme

The EU Nitrates Directive (EC, 1991) has been implemented in Ireland since 2007 and regulates agricultural practices related to the Water Framework Directive, such as stocking rate, fertiliser use, organic manure storage requirement, and timing of manure and fertiliser application. The newly proposed EU Green Deal (EU, 2019) Farm to Fork strategy has set a target to reduce nutrient losses by at least 50% and fertilizer use by at least 20% by 2030.

The 5th Nitrate Action Programme has just introduced a significant number of new actions designed to reduce nutrient loss to surface waters and groundwater and improve water quality. Most of these came into effect on the 11th of March 2022 with some of the remaining measures (nitrogen register and banding relating milk yield and related organic N) due to be implemented in 2023. The most significant changes include:

- Slurry, soil water storage and management, plus prohibited period of application:
    - From 1st December 2023, all milk producers must have a minimum of 21 days soiled water storage capacity on the holding;
    - From 1st December 2024, all milk producers must have a minimum of 31 days soiled water storage capacity on the holding except for winter/liquid milk producers where this storage must be in place by 1st December 2025;
    - The closed period for slurry spreading has been extended to commence on 8th October in 2022 and on 1st October from 2023 onwards.
    - Closed period for chemical fertiliser extended to 15th of September to the 26th of January in Zone A; 15th of September to the 29th of January in Zone B; 15th of September to the 14th of February in Zone C and D.
- Livestock excretion rates – three new excretion rate bands are being introduced for the dairy cow from 2023; 80 kg N/cow (<4,500 kg milk/cow), 92 kg N/cow (4,501 to 6,500 kg milk/cow) and 106 kg N/cow (>6,501 kg milk/cow).
- Chemical fertiliser control – a 10% reduction to the maximum chemical N fertiliser application on grassland in 2022 with an additional proposed 5% reduction in 2024.
- Crude protein in concentrate feeds – on holdings with grassland stocking rates of 130 kg N/ha or above, a maximum crude protein content of 15% is permitted in concentrate feedstuff fed to dairy cows between 15th April and 30th September.

- Register of chemical fertilizer sales to be established by the Department of Agriculture, Food and the Marine for 2023.

Additional to these changes the recent published Food Vision Dairy and Food Vision Beef and Sheep reports recommend significant further fertiliser N reductions between now and 2030 (27-30%). These changes while not agreed by all stakeholders form the basis of a significant component of the GHG emissions reductions to be achieved at farm level.

There is a variable hydrologic and biogeochemical time lag (months to decades) between N losses and changes to water quality and this must always be acknowledged when considering the efficacy of programmes and measures. These are significant changes and they will require a significant time period to be implemented at farm level and the subsequent responses to be realised in water bodies. Introducing a further significant change by reducing the maximum stocking rate from 250 kg N/ha to 220 kg N/ha will not permit the effectiveness of the 5th NAP measures outlined above and the chemical nitrogen reduction in the Food Vision Dairy/Beef and Sheep Reports to be properly assessed. The modelling outlined below points to a very significant impact on N leaching of these measures.

1.4. Competitiveness of farming system

In grass-based systems there is a very strong relationship between overall farm financial performance and grass utilised per hectare (Hanrahan *et al.,* 2018). The two key drivers of grass utilisation are stocking rate and supplementary feed levels. Any strategy that reduces overall stocking rate below the grass growth and utilisation capacity of the farm (Table 1) will reduce farm profitability and could change the focus of the system, effecting the economic sustainability of pasture based systems.

Increased grass utilisation has accounted for 69% of the increase in productivity in Irish dairy farms between 2010 and 2020 (Dillon *et al.,* 2020). The number of grassland farmers using PastureBase Ireland has increased significantly in recent years (figure 2). Knowledge of farm grass cover (grass availability on farm) and current grass growth rates has led to more efficient use of grazed grass. Additionally, increased grass production combined with higher grass utilisation will result in increased N use efficiency. The average grass production on dairy farms, using PastureBase Ireland data, is greater than 14 t DM/ha, facilitating a farm stocking rate of 2.5 cows/ha (assuming a concentrate supplementation level of 500 kg/cow and an organic N per cow of 92 kg) or >2.6 cows/ha with current national feeding levels. For grassland farmers that can produce greater than 14 t DM/ha, the appropriate stocking rate will be > 2.6 cows per hectare with current national feeding levels. It is also anticipated that the imposition of lower stocking rate limits (below 250 kg organic N/ha) will increase competition for land rental, thereby, bringing additional land into dairy production, and displacing other enterprises. There is already anecdotal evidence that this is the response of some farmers who are moving in the top band for livestock excretion rate.

Reducing the maximum stocking rate from 250 kg N/ha to 220 kg N/ha on top of a reduction in stocking rate associated with the general increased organic N per cow as a result of banding will result in reduced pasture utilisation which would be expected to result in reduced farm profitability on Irish farms (Hanrahan *et al.,* 2018). There is a very high risk that if farms at higher stocking rates are constrained in cow numbers, they will increase milk yield per cow through increased feed imports or growing of maize silage. This will result in a reduction in the food security of the system (i.e. requirement for more concentrate/purchased feed per cow), which will result in a higher N surplus at farm level (which is associated with an increased risk of N loss) leading to a reduction in farm profitability. It is also likely that where dairy farms rent or lease additional land primarily to meet organic N limits, there will be uneven distribution of nutrients within the overall farm. This will give rise to uncertain outcomes regarding N leaching and will further limit the impact of changes to organic N limits.

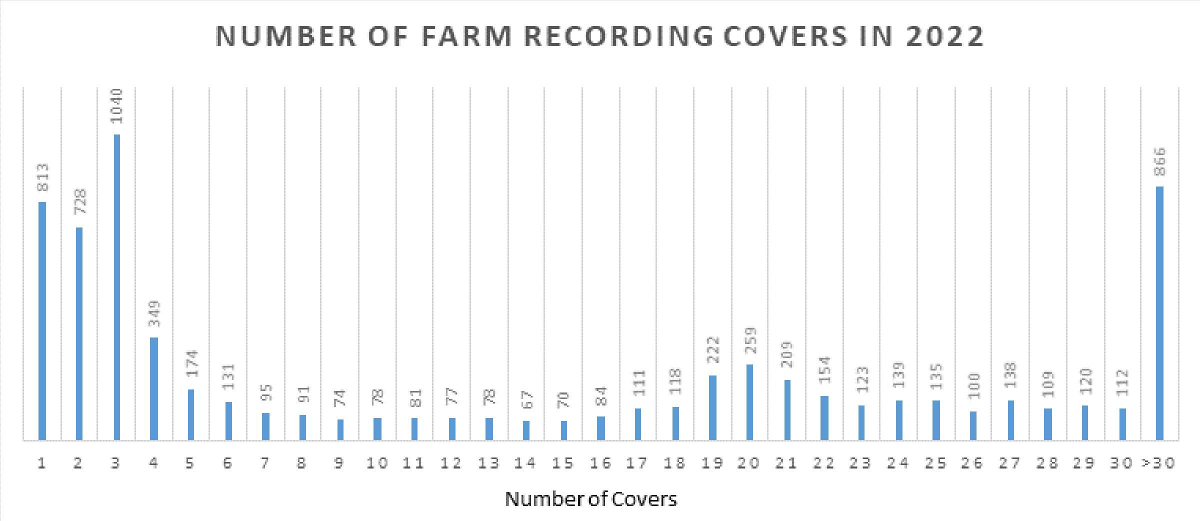
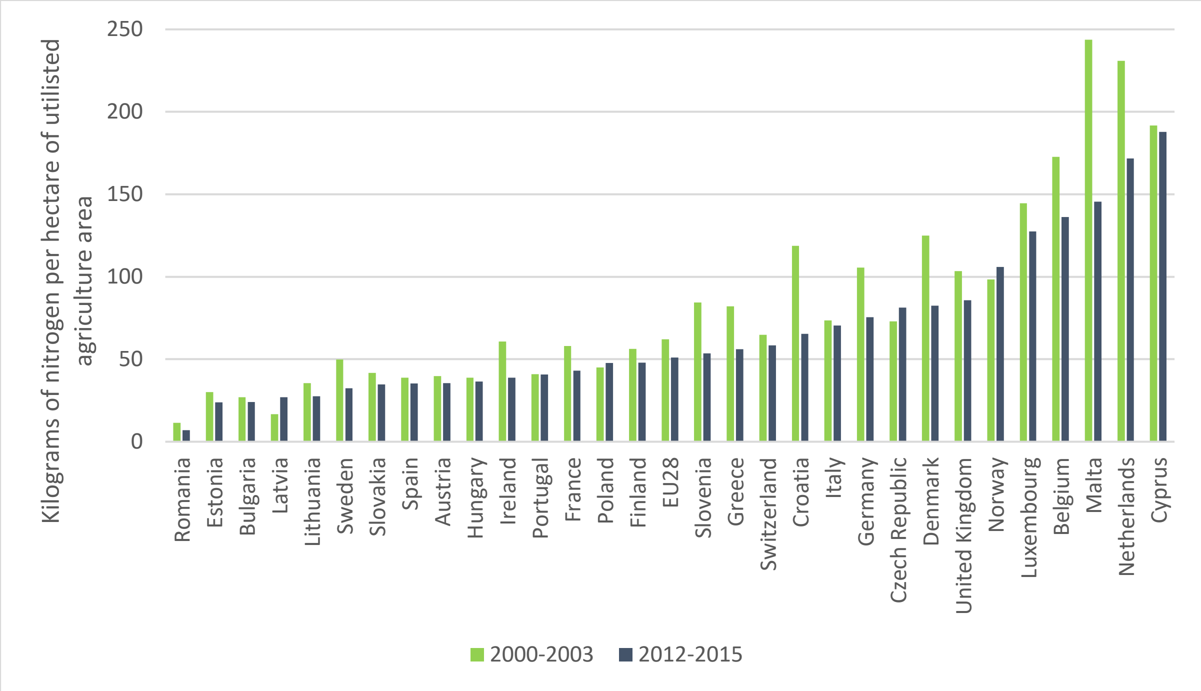


Figure 2. Numbers of farmers recording farm cover and the number of covers recorded on PastureBase Ireland in 2022

1.5 Nitrogen use efficiency and surplus

A recent study evaluated system across countries for nitrogen surplus and nitrogen use efficiency (NUE) (Quemada 2020). This analysis showed that there is substantial differences in NUE and N surplus across farming system and management. Arable farms had lower N inputs and surplus and had therefore higher NUE than livestock farms. The study found that if comparing livestock systems without including the nitrogen embedded in the brought in inputs (bought in concentrate) could result in an inaccurate determination of system efficiency. The study showed that when the NUE was calculated at a farm level without taking into account the externalisation of feed and the export of manure that the Dutch had the highest NUE and N surplus relative to France, Denmark with Ireland having the lowest NUE. However, when the externalisation of feed and slurry was taken into account there was no difference in NUE across the four countries. This study shows that comparison across system and country should be completed with careful consideration of all of the factors. It should be coupled with consideration of the system and, for example, likelihood of fallow ground over the winter period and the period where nutrients are being taken up by plant growth in a pasture based system.

Figure 3 shows the gross N balance by country in the EU for 2000 to 2003 and 2012 to 2015. Over the period, EU 28 average gross N balance reduced from 62.2 to 51.1 kg/ha for utilized agriculture land; the corresponding reduction for Ireland was 60.8 to 38.8 kg/ha of utilized agriculture land. Therefore, over this period gross N balance reduced by 11 kg/ha on average in the EU, while gross N balance in Ireland reduced by 22 kg/ha. Additionally, it shows that over the period 2012 to 2015 Ireland gross N balance was significantly lower than the EU average (12.3 kg/ha) despite the fact that Ireland has a relatively small arable area. This is achieved by the grass based system and the relative extensive nature of livestock production in Ireland despite the fact that individual farmers across the country operate with a nitrates derogation.



Data source: Eurostate Gross Nutrient Balance, b. EEA_Indicator SEB1019

Figure 3. Gross nitrogen balance by country

Note: Eurostat estimates are used for one or more years for Belgium Bulgaria, Croatia, Cyprus, Denmark, Estonia, Greece, Italy, Latvia, Lithuania, Luxembourg, Malta and Romania.
For Estonia for the period 2000-2003, the average of the years 2004, 2005 and 2006 was used.
For the EU-28, EEA calculations are based on Eurostat data

2. Water quality in the Agricultural Catchments Programme

Water quality is regulated in the EU and Ireland by the Water Framework Directive (WFD; EC, 2000), which requires at least “good” water quality in all EU water bodies (rivers, lakes, groundwater, and transitional coastal waters). In Ireland, this must be achieved by 2027.

The ecological status of Irish surface waters and groundwater are better than most EU countries, with 53% of Irish surface waters having a good or high status compared with 44% in EU and 92% of groundwater being good compared with 80% in the EU (Wall *et al.,* 2020). The latest EPA report (EPA, 2022) showed that 54% of Irish surface waters were in high or good ecological status and 92% of groundwater are in good chemical status over the period 2016-2021. It is important to note that this reporting period coincided with the prolonged drought in 2018 (grass DM production declined by 3 t DM/ha nationally), which resulted in elevated nitrate-N concentration in surface and groundwater as shown in the analysis of data from the ACP.

It is acknowledged that there is a requirement to improve water quality in Ireland. From within the agriculture sector, this will be best achieved by reducing excess nutrient nitrogen and phosphorous loss, which result in excessive growth of plant and algae leading to low oxygen levels and affects macroinvertebrates. The Agriculture Sustainability Support and Advisory Programme (ASSAP) is focusing on the priority areas for action based on water quality in particular areas across the country. It is a new, free advisory service with 38 advisors working in 190 catchments, which started in 2018. The ASSAP programme is focused on addressing agricultural pressures on streams and will focus on advisors working closely with farmers. Where an agricultural pressure is identified, the farmers in the area will receive the offer of a free farm visit from an ASSAP advisor. The purpose of the visit is to meet with the farmer and assess the farm for any potential issues that may be having an effect on the water quality in the local catchment. The most recent EPA water quality report has shown significant progress in relation to increasing water quality within priority areas that are part of the ASSAP programme.

The Agricultural Catchments Programme (ACP) has carried out extensive research in six river catchments ranging in size from 4–30 km^2, which have been continually monitored for a range of biophysical parameters since 2008. The catchments were selected to represent intensively managed agricultural land on different physical settings and dominating land use, and, therefore, represent a range of different type of riskiness for N (and P) loss in terms of vertical drainage or lateral runoff risk (Table 2). A decade of studies within the ACP was recently summarised in a review paper citing 67 research papers by the ACP published in international journals (Mellander *et al.,* 2022).

The high frequency monitoring of N concentration in the catchment’s outlets have shown that not only the magnitudes of concentrations but also the dynamics varied across the catchments. The link between the percentage of land in derogation and the stream water concentration of nitrate-N was not clear, reflecting differences in soil type, land-use and meteorological factors which were evident at the catchment scale of the ACP. For example, Castledockerell has the highest nitrate-N concentration in stream water, despite having the lowest stocking rate organic N (with only 5% of the catchment in derogation). The ACP research has found that, in general, physical settings tend to override source pressure in terms of nutrient export risk. This highlights the overriding importance of soil type, subsoil geology and groundwater hydrochemistry in controlling N (and P) losses to water (Jordan *et al.,* 2012; Mellander *et al.,* 2012; Shore *et al.,* 2016).

Table 2. Dominating catchments characteristics, annual average stocking rate (organic N load 2010-2018) and annual average river flow and N load in the river (2010-2020)							
Catchments Characteristics				**Annual Inputs**		**Annual Outputs**	
Name	**Land Use**	**Soil drainage**	**Size (km^2)**	**Rainfall (mm)**	**Stock. rate org N (kg ha^{-1})**	**Stream flow (mm)**	**In-stream NO_3-N (kg ha^{-1})**
Corduff	Grass	Poor	3	1,056	87	562	7.9
Dunleer	Arable/Grass	Moderate	10	872	67	420	23.4
Ballycanew	Grass	Poor	12	1,044	101	512	13.4
Castledockerell	Arable	Well	11	1,009	41	528	37.3
Timoleague	Grass	Well	8	1,097	166	666	41.3
Cregduff	Grass	Well	31	1,220	90	172	2.2

To assess the temporal trends in N export rates within ACP catchments, a Mann-Kendal inter-annual trend test was carried out over the 2010–2022 annual nitrate-N concentration. This analysis was carried out over 4-year rolling periods (the minimum number of years required for this method), as well as over the whole 12-year period (Table 3 and Figure 4). Over the last 4-year rolling periods (2019 to 2022) there is a decreasing trend in nitrate-N concentrations in the Timoleague catchment, stable in the Dunleer and Corduff and no tend in the Ballycanew , Castledockerell and Cregduff.

Table 3. Annual average nitrate-N concentration (mg/l) and the four-year Mann-Kendal inter-annual trends are indicated with symbols : -- = no trend, = stable (no change), = ↑ increasing and ↓ = decreasing						
Land –Use:	**Grass**	**Grass**	**Arable**	**Grass**	**Grass**	**Grass**
Drainage:	**Poor**	**Well**	**Well**	**Moderate**	**Poor**	**Well**
YEAR	***Ballycanew***	***Timoleague***	***Castledockerell***	***Dunleer***	***Corduff***	***Cregduff***
2010	2.29	5.00	6.22	4.95	1.15	1.36
2011	2.34	5.39	6.48	4.48	1.17	1.65
2012	2.98	6.30	7.13	5.82	1.13	1.19
2013	2.56	5.64	7.21 ↑	4.57 →	1.20	1.14 →
2014	2.50 →	5.45 →	7.15	5.33	1.11 →	1.46 →
2015	2.53 →	7.07 →	7.37	5.22 →	1.25	1.61
2016	2.50 →	5.57 →	7.02 →	3.93 →	0.92 →	0.93 →
2017	2.91	6.49 →	7.42	4.40 →	1.35	1.34 →
2018	2.91	6.64→	7.41	6.37	2.13	1.21 →
2019	2.73→	7.15 ↑	7.22 →	8.44 ↑	2.30 ↑	1.39
2020	2.27↓	6.30 →	6.96 ↓	5.93	1.43	1.01 →
2021	2.48 →	5.43 →	6.66 ↓	5.51 →	2.20 →	1.05 →
2022	2.85	4.95 ↓	-	6.06 →	2.28 →	1.80 →

No trend Stable Increasing Decreasing

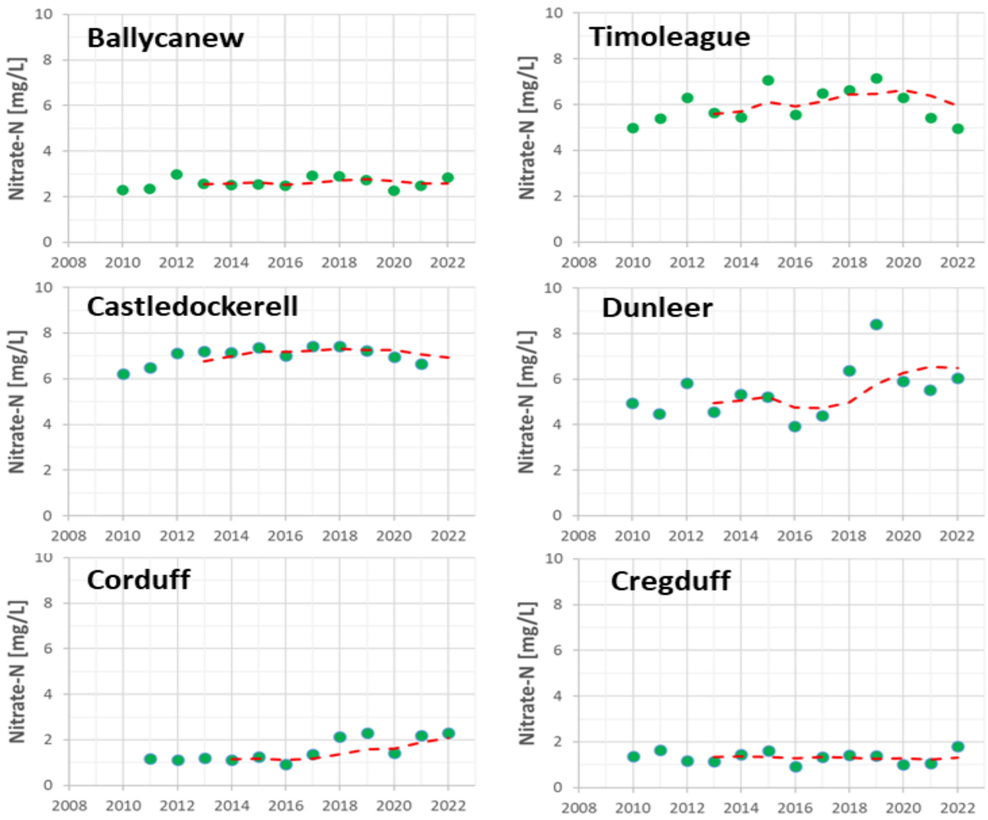


Figure 4. Twelve years of annual average nitrate-N concentration (symbols) and four-year antecedent moving average (line) in the six catchments monitored in the ACP

Over the whole 12-year period, the nitrate-N concentration was below the Environmental Quality Standards (EQS) in Corduff, but with an increasing trend. Timoleague had an elevated nitrate-N concentration (above the EQS), largely driven by 2018/2019, but since has reduced. Cregduff had a stable trend and a nitrate-N concentration well below the EQS. While the concentration was just below the EQS in Ballycanew, it was above the EQS in Castledockerell and Dunleer. In those three catchments there was no trend over the twelve years.

To examine in greater detail the complexity of varying soil types, as well as the range of agronomic intensities existing even within small-scale catchments (ca. 10 km^2), a sub-catchment approach was also utilized. Two hydrologically contrasting catchments with a high percentage of land in derogation (Timoleague and Ballycanew) were divided into eight nested sub-catchments (*ca.* 1 km^2) corresponding to the water quality monitoring sites along the river network. Sub-catchments dominated by land in derogation and with minimum amount of land in derogation were selected for comparison of nutrient concentrations in the stream water.

In Ballycanew, the catchment with mostly poorly drained soils, the percentage of land in derogation was not reflected in the nitrate-N concentrations monitored in the stream water of the sub-catchments, despite a large difference in the percentage of land in derogation (Table 4). Additionally, two sub-catchments (T2 and M1) had substantially increased in the percentage of land in derogation from 2014-2018 (from 0-46% and 11-57%, respectively), and this sharp increase was not detected in the stream water of those sub-catchments. By contrast, in the Timoleague catchment (which has freely drained soils) the sub-catchment with a higher percentage of land in derogation had higher concentrations of nitrate-N (and TRP) in the stream water, but in recent years has reduced (Table 4).

Research has also been carried out at ACP sites to assess the connection between source loading and groundwater N concentrations in two catchments which are freely draining, but otherwise contrasting (i.e. Timoleague and Castledockerell). At the catchment scale there was a poor link with the surplus nitrate-N leached to the groundwater and the concentrations of nitrate-N monitored in the catchment river outlet, and the N removal capacity varied highly between and within two of the catchments monitored (McAleer *et al.,* 2017).

Table 4. Proportion of land in derogation in Ballycanew and Timoleague catchment and average Nitrate-N concentration for the period 2010-2018 at the outlet, and for selected sub-catchments

Ballycanew	Outlet	Sub-Catchment			
		M5	M6	M1	T2
Derogation [%]	34%	3%	0%	39%	27%
Nitrate-N [mg l^{-1}]	2.6	3.4	3.04	2.36	3.23
Timoleague	**Outlet**	**Sub-Catchment**			
		M5	**T1A**		
Derogation [%]	80%	12%	80%		
Nitrate-N [mg l^{-1}]	5.97	4.24	5.73		

In the Timoleague catchment, there was a high annual organic N loading with an increase from 134-182 N kg/ha in the 2008-2018 period, but there was no statistically significant temporal trend found in the groundwater nitrate-N concentration during the 2010-2017 period (McAleer *et al.,* 2022) and when the period up to 2022 is evaluated is showing a reducing trend. In the Castledockerell catchment, which was dominated by spring barley, there was a low annual organic N loading with a minor increase from 35-45 kg N/ha from 2008-2018, and there was a higher groundwater nitrate-N concentration with a positive trend during the 2010-2017 period (McAleer *et al.,* 2022).

It was found that factors such as N application, soil moisture deficit, and soil/bedrock permeability explained 60-80% ($P<0.0001$) of the nitrate occurrence in the groundwater suggesting that it was not possible to separate agronomic factors from hydrogeological or meteorological ones. Despite having lower sources, Castledockerell catchment had high nitrate-N concentrations in both groundwater and surface water due to a combination of free draining soils, lower drainage, and tillage management practices (McAleer *et al.,* 2022). For example, in one of the catchment monitoring sites the nitrate-N concentration in the shallow groundwater locally reached highly elevated levels of 23.9 mg/L as the result of a ploughing and pasture reseeding event. This was, however, not detected in the river due to the locally high N removal capacity and likely also due to mixing of deeper groundwater with lower nitrate-N concentrations (Mellander *et al.,* 2014).

The lack of a consistent direct connection between source pressures and (sub)-catchment export of N can be attributed to the site characteristics of the individual sites considered. The Irish agricultural landscape is heterogeneous in terms of its physical setting and even within smaller catchments (*ca.* 10 km^2), such as those monitored within the ACP, there can be a large variability in soil types and the factors controlling both N and P transfer pathways and the transformation processes (such as topography, soil, and bedrock properties – mainly permeability). Such factors include both static (e.g. soil and bedrock type, thickness, and permeability) and dynamic factors (e.g. climate, soil moisture deficit, depth to water table) which are spatially and temporally variable across any farming landscape (Fenton *et al.,* 2017; Huebsch *et al.,* 2013; Mellander *et al.,* 2018).

Amplified cycles of weather can largely influence N loss to water and the influence is different within the agricultural landscape due to the physical and chemical settings (Mellander *et al.,* 2018). In some catchments, inter-annual increasing trends were observed, while there could also be inter-seasonal increasing or decreasing trends that influenced or counteracted these inter-annual trends (Mellander and Jordan, 2021). Additionally, changes occurring to rainfall intensity and soil temperature patterns were found to be important drivers of nutrient mobility in soils (Mellander and Jordan, 2021).

For example, in 2018 a nation-wide drought caused a build-up of a large soil N pool due to poor grass growth and enhanced soil N mineralisation as well as poor fertiliser management. That pool of N was flushed out and transferred to the stream in the large rain events in November causing elevated nitrate-N concentrations (Mellander and Jordan, 2021). The influence of this weather extreme was clearly seen in the ACP catchments where the monthly average nitrate-N concentrations increased in all catchments and in Dunleer catchment exceeded the WFD drinking water standard threshold concentration of 11.3 mg nitrate-N/L. The daily average nitrate-N concentration also exceeded the WFD threshold in the Ballycanew catchment which in other times has a relatively low nitrate-N concentration.

The long-term shifts in weather patterns and more frequent weather extremes, as expressed by the North Atlantic Oscillation Index, was found to influence both N (and P) concentration in the ACP catchments and in similar sized (ca. 10 km^2) agricultural catchments in Norway and Brittany (Mellander *et al.,* 2018). The response was different for catchments with different physical and chemical settings, and there were also impacts to pollution patterns of extreme weather including short periods of rain induced nutrient flux that exceeded average annual mass loads in these catchments, and drought influences on point source pollution (Mellander and Jordan, 2021).

The connection between source loading and N export rates will also be impacted by inherent temporal lags in catchment response. Expected water quality improvement as the results of mitigation measures may be delayed for groundwater due to variable drainage amounts and delayed responses of nitrate in deep aquifers (Fenton *et al.,* 2011). In meso-scale catchments, a positive response occurred from 1-10 years after decreased N surpluses were achieved, with the response time broadly increasing with catchment size (Melland *et al.,* 2018). However, it took from 4-20 years to confidently detect the effects in water body monitoring systems. Such time lag may be a useful indicator to reveal the hydrogeological links between the agricultural pressure and water quality state, which is fundamental for a successful implementation of any water protection plans (Kim *et al.,* 2020).

3. MoSt GG –PBHDM modelling approach

In order to determine the impact of year, fertilizer N level and maximum Organic N levels a modelling approach was deployed. Two separate modelling approaches were used in order to increase the confidence of the model outputs. The MoSt GG/PBHDM (Moorepark and St Giles Grass Growth Model/Pasture Based Herd Dynamic Milk Model) is a dynamic mechanistic model that simulates a range of physical characteristics with a daily time step while the €riN model is a budgetary simulation model operating at a monthly time step. While both approaches generated N outputs and losses the MoSt GG/PBHDM modelling approach specialized on the impact of weather, chemical N and organic N/ha on grass growth, farm feed budget and N use efficiency. The €riN model specialized on the impact of chemical N and organic N/ha on N use efficiency and gaseous N emissions.

3.1. Methodology

Table 5 shows the chemical N application strategy used in the various scenarios simulated. The MoSt Grass Growth model (Ruelle *et al.,* 2018) is a mechanistic model that uses weather, soil type and management information to simulate grass growth with a daily time step. The weather data was recorded by the Met Éireann weather station located at Moorepark (52°09'52.3"N 8°15'36.6"W) over a 19 year period (2003-2021). Each of the simulations was completed on a daily time step for those 19 years consecutively meaning that weather or management happening in one year could have consequences (for example N still available for leaching) in the subsequent year. In this analysis it was assumed that soil type was free draining and therefore that would have implications for the likelihood of N leaching. A previous report (Dillon *et al.,* 2021) showed that leaching was significantly higher on a free draining soil when compared to a heavier soil.

The Pasture Based Herd Dynamic Milk model (PBHDM) (Ruelle *et al.,* 2015) is a mechanistic model of a dairy system taking grass growth information from the MoSt GG model and using this information when feeding and managing the animals. In this analysis the model simulated a high level of grassland management practices, dairy cow nutrition and slurry management. Concentrate was fed at 3.5 kg DM per cow per day for the first 40 days of lactation and 2.0 kg DM per cow per day afterward irrespective of the amount of grass on the farm. Indoors lactating cows were fed grass silage ad libitum (quality 1.1 FV, 0.78 UFL, 75 PDI), while dry cows were allocated 80% of ad libitum intake of a lactating cow to meet energy requirements for maintenance, pregnancy and body condition score change (circa 10 kg silage DM per cow per day). During the grazing season cows were housed when the soil saturation level was over 90%. Grazing management was dictated by both pre- and post-grazing height, while farm grass cover was evaluated daily and was compared with herd requirement. In a situation where farm grass cover was greater than target, surplus paddocks were removed as silage. In a situation where grass supply was not adequate, areas closed for silage were brought back into grazing. In a grass deficit situation, extra concentrate was fed up to 4.0 kg DM per day per cow (on top of the base concentrate); if grass supply was still in deficit, grass silage was fed up to a maximal rate of 6.0 kg DM/cow. In the simulations, priority was given to grazing over silage conservation; if silage produced on the farm was in deficit, it was purchased.

The PBHDM simulated the number of days at grazing, the number of days at grazing without additional supplementation, grass intake (kg/cow and kg/ha), silage intake (while cows are grazing, while lactating cows are indoors due to soil saturation and while cows are dry and indoors; kg DM/cow and kg DM/ha), milk, protein and fat produced (kg/cow and per ha), the amount of silage produced (kg/ha) and yearly surplus or deficit of silage (kg/ha). All outputs were simulated per day and were then summarised by week, season, year or over the full period.

3.2. Scenarios

3.2.1. Influence of year on grass growth, feed budget and N flows

Table 6 shows the influence of year on grass growth; feed budget and N flows from pasture grazed by dairy cows stocked at 2.5 cows/ha using 225 kg chemical N fertiliser/ha on a free draining soil. It can be observed that there is significant year-to-year variability in all of the factors modelled with no change in management. This is because of weather variability from year-to-year and highlights the requirement of dynamic management at farm level to minimise loss in those periods. Years 2006 and 2018 had the greatest N surplus/ha; while years 2007 and 2017 had the lowest N surplus/ha. In 2006 and 2018, grass growth rates were lowest, requiring higher concentrate supplementation/cow as well as a requirement to import a large proportion of the grass silage per cow. In contrast, grass growth was high in 2007 and 2017, requiring lower levels of concentrate feeding and there was a surplus of silage produced.

3.2.2. Chemical N application and SR

In all the simulations carried out, the farm area was 40 hectares. Different chemical N application strategies were simulated. The base scenario was based on a chemical N application rate of 225 kg N/ha being applied from the start of February to the 15th of September. The timings of the chemical N applications are shown on Table 5.

Table 7 shows the influence of chemical N application rates of 250, 225, 200 and 175 kg N/ha on grass growth, the feed budget and nitrogen flows to one meter depth. In addition, 4 different stocking rates were simulated (for each of the chemical N applications rates): 2.94 cows/ha corresponding to 271 kg organic N/ha (corresponding to the highest allowed SR when the organic N/cow was based on 85 kg recalculated based on an organic N of 92 N/cow); 2.73 cows/ha corresponding to 250 kg organic N/ha, 2.50 cows/ha corresponding to 230 kg organic N/ha and 2.39cows/ha corresponding to 220 kg organic N/ha (Table 7).

Table 5. Chemical N application strategy use in the various scenarios simulated on dairy farm

Year	Fertiliser level variation			
Total N applied	250	225	200	175
February	29	26	23	20
March	43	39	34	30
April	41	37	33	29
May	39	35	31	27
June	35	32	28	25
July	22	20	18	15
August	24	22	19	17
September	17	15	14	12

3.2.3. Financial implications

Table 8 shows the impact of reduced chemical N where cow numbers were fixed and where feed was purchased onto the farm to fill the feed deficit due to the reduced grass growth. Spend on purchased feed on the farm increased by €4,239, €8,322 and €12,388 for reductions in chemical N fertiliser of 25, 50 and 75 kg N/ha, respectively. In this scenario, reducing chemical N fertiliser reduces grass growth thereby creating a situation where a relatively cheap feed (grazed grass) is being replaced with a much more expensive feed (grass silage and concentrates). Strategies to minimise the effect on profitability would include a focus on soil fertility and the widespread introduction of clover to the farm.

3.2.4. Influence of year on N leaching, N surplus

Table 6 shows the grass growth, feed budgets and N flows for each of the 19 years simulated. Over the 19-year period, keeping the farming system unchanged, the quantity of N leached that was simulated varied from 37.1 kg N/ha to 83.4 kg N/ha, with an average of 59.4 kg/ha reflecting inter-annual weather effects on leaching.

3.2.5. Chemical nitrogen in the spring

Moving the spring applications of nitrogen from a scenario where the first spreading was in mid-January to the start of February reduced N leaching by 0.5 kg/Ha and had no impact on N surplus.

3.2.6. Chemical nitrogen application

On average, across all of the SR scenarios, reducing chemical N application rates from 250 to 225 kg N/ha, from 250 to 200 kg N/ha and from 250 to 175 kg N/ha, reduced modelled N leaching to one metre depth by 2.3%, 4.5% and 6.5%, respectively; N surplus was reduced by 8.6%, 17.2% and 25.6%, respectively (Table 7). Overall, farm profitability was reduced by €4,622, €8,951 and €12,861 at chemical N rates of 225, 200 and 175 kg N/ha, respectively. Net profit per hectare was reduced by €116/ha, €224/ha and €322/ha (Table 8), respectively.

Table 6. Influence of year on grass growth; feed budget and N flows simulated from pasture grazed by dairy cows stocked at 2.5 cows/ha using 225 kg chemical N/ha on a free draining soil

Year	Grass growth (kg D,M/ha)	Grass intake (kg DM/cow)	Silage intake (kg DM/cow)	Concentrate (kg DM/cow)	N leaching (1m) (kg/ha)	MS (kg/cow)	Silage balance (kg DM/ha)	N surplus (kg/ha)	Rainfall (mm/year)
2003	14,415	3,191	1,055	852	45.5	412	1,044	176	882
2004	13,974	3,445	987	839	64.7	434	2	194	1,032
2005	13,427	3,432	942	853	58.3	431	-20	196	1,028
2006	9,421	2,448	1,705	1,357	58.4	445	-3,141	296	1,094
2007	14,605	3,474	915	827	44.0	431	712	178	918
2008	13,240	3,339	1,044	887	72.3	434	-257	203	1,052
2009	14,220	3,436	989	825	83.4	431	225	189	1,293
2010	13,702	3,276	1,117	930	37.1	437	-6	200	869
2011	14,234	3,349	1,041	890	39.0	433	150	194	856
2012	13,178	3,417	960	827	75.2	429	-199	198	1,097
2013	11,484	2,954	1,315	1,135	47.1	439	-1,587	248	946
2014	14,563	3,417	1,019	854	74.4	436	555	182	1,239
2015	14,265	3,275	1,087	907	71.9	434	224	194	1,209
2016	13,241	3,228	1,125	989	47.1	443	-364	211	979
2017	14,662	3,508	902	790	60.6	429	596	178	1,015
2018	9,025	2,312	1,804	1,367	72.4	440	-3,365	303	**1,078**
2019	14,972	3,439	958	782	65.2	424	970	171	**1,082**
2020	14,487	3,485	939	821	59.6	436	523	181	1,100
2021	13,644	3,380	974	870	51.7	432	-16	197	999
Max	14,972	3,508	1,804	1,367	83	445	1,044	303	1,293
Min	9,025	2,312	902	782	37	412	-3,365	171	856
Avg	13,408	3,253	1,099	926	59.4	433	-208	205	1,040

Table 7. Influence of chemical N application rate on grass growth, feed budget and nitrogen flows to 1 meter depth from pasture grazed by dairy cows, at a stocking rate of 271, 250, 230 and 220 organic N per hectare on a free draining soil (40 ha)										
Nitrogen (kg/ha)	**Organic N (kg/ha)**	**No. cows**	**Grass growth (kg DM/ha)**	**Grass intake (kg DM/cow)**	**Silage intake (kg DM/cow)**	**Con. intake (kg DM/cow)**	**N leaching (1m) (kg /ha)**	**Milk solids (kg MS/cow)**	**Silage Balance (kg DM/ha)**	**Nitrogen surplus (kg N/ha)**
250*	271	118	13,855	3,217	1,115	933	62.7	432	-645	238
225*	271	118	13,506	3,191	1,132	951	61.4	433	-872	219
200*	271	118	13,142	3,168	1,146	970	59.9	434	-1,113	200
175*	271	118	12,761	3,116	1,192	990	58.7	434	-1,391	183
250	271	118	13,871	3,202	1,123	941	62.2	432	-627	238
225	271	118	13,525	3,185	1,133	961	60.8	433	-853	219
200	271	118	13,148	3,180	1,142	968	59.5	435	-1,120	200
175	271	118	12,767	3,137	1,175	992	58.3	435	-1,379	182
250	250	109	13,768	3,262	1,091	921	60.7	433	36	224
225	250	109	13,408	3,253	1,099	926	59.4	433	-208	205
200	250	109	13,032	3,230	1,113	945	58.0	434	-459	186
175	250	109	12,635	3,198	1,135	964	56.8	435	-727	168
250	230	100	13,647	3,336	1,049	871	59.2	432	699	209
225	230	100	13,285	3,295	1,069	901	57.8	433	476	190
200	230	100	12,905	3,279	1,084	907	56.5	433	212	171
175	230	100	12,499	3,250	1,104	924	55.3	434	-58	153
250	220	96	13,602	3,350	1,030	867	58.5	431	1,030	202
225	220	96	13,231	3,309	1,051	890	57.1	431	799	184
200	220	96	12,849	3,281	1,076	907	55.8	432	531	166
175	220	96	12,435	3,270	1,084	912	54.5	433	251	147

* Half of the February application has been applied in January to highlight the previous N pattern.

Table 8. Influence of chemical N application rate on the financial performance on a 40 ha dairy farm based on holding cow numbers constant					
		250	**225**	**200**	**175**
Physical	Cows	110	110	110	110
	Milk produced (kg)	601,520	601,520	601,520	601,520
	Stocking rate (cows/ha)	2.63	2.63	2.63	2.63
	MS sales (kg)	50,010	50,010	50,010	50,010
Receipts	Milk receipts	213,267	213,267	213,267	213,467
	Livestock receipts	23,746	23,746	23,746	23,746
	Total receipts	**237,013**	**237,013**	**237,013**	**237,013**
Variable costs	Purchased feed	13,251	17,490	21,573	25,639
	Fertiliser	14,400	13,615	12,843	12,016
	Replacement costs	20,973	20,973	20,973	20,973
	Veterinary and AI	11,465	11,465	11,465	11,465
	Silage	5,409	5,859	5,951	6,094
Fixed costs	Labour	24,617	25,341	26,065	26,789
	Depreciation	14,752	14,752	14,752	14,752
	Interest	8,029	8,029	8,029	8,029
	Electricity	3,230	3,230	3,230	3,230
	Insurance	9,040	9,040	9,040	9,040
	Total costs	**143,989**	**148,617**	**152,943**	**156,850**
Net profit*	Per farm	93,071	88,449	84,120	80,210
	Per hectare	2,327	2,211	2,103	2,005

3.2.7. Reducing organic N from 250 to 220

On average, across all of the fertiliser levels, reducing organic N/ha from 271 kg (2.94 cows/ha) (previous stocking rate when organic N per cow was assumed to be 85 kg) to 250 kg (2.73 cows/ha) to 230 kg (2.53 cows/ha) to 220 kg (2.39 cows/ha) reduced N leached by 2.4%, 5.0% and 6.2%, respectively (Table 7). It also reduced N surplus by 6.8%, 14.0% and 17.0%, respectively. Table 9 shows the effect of organic N/ha on farm profitability. The influence of different organic N/ha levels were modelled which included 250, 230 and 220 kg N on the profitability of a 40 ha dairy farm. The analysis was completed where there was no hired labour on the farm and it resulted in a net profit of €96,211, €88,073 and €83,730 at a farm organic N level of 250, 230 and 220 kg of N per hectare. The impact for a farmer that is currently stocked at 250 kg N/ha, having to reduce to 230 or 220 kg N/ha was simulated by maintaining some of the fixed costs as cow numbers reduced. When this occurred the farm net profitability was €96,211, €86,380 and €81,291, or a reduction of €246 and €373 per hectare, respectively. When the same analysis was completed with a base milk price of €0.50/l at 3.3% protein and 3.6% fat, farm profitability was reduced by over €500/ha when organic N output per hectare was reduced from 250 to 220 kg N/ha.

3.2.8. Policies agreed or planned to be implemented

A number of changes to the Nitrates Action Plan regulations have already been implemented or will be implemented in the near future around reducing stocking rates and chemical N fertiliser application levels. These changes include the reduction in organic N from 271 kg N/ha to 250 kg N/ha based on actual organic N excretion rates, reduction of chemical fertiliser by 10% under nitrates regulations or (27% to 30%) under the Food Vision plans as well as reduced N applications in the month of January. The combined effects of these regulatory changes is estimated to reduce nitrate-N leaching to one metre level by 5.9 kg/ha (reducing organic N from 271kg/ha to 250kg/ha, delaying fertiliser N in January, reducing fertiliser N levels by 30% (Table 7)) . These changes are not yet implemented at farm level or have not had an opportunity to have an effect on nitrates loss and ultimately water quality.

Table 9. Influence of platform stocking rate (kg organic N/ha) on the financial performance on a 40 ha dairy farm				
Organic N (kg N/ha)		**250**	**230**	**220**
Physical	Milk platform (ha)	40	40	40
	Cows	110	101	97
	Milk produced (kg)	611,820	559,742	539,514
	Stocking rate (cows/ha)	2.72	2.50	2.41
	MS sales (kg)	46,416	42,461	40,930
Receipts	Milk receipts	199,907	182,877	176,281
	Livestock receipts	32,270	29,629	28,456
	Total receipts	**232,176**	**212,506**	**204,737**
Variable costs	Imported silage costs	0	-2,447	-3,537
	Fertiliser	12,958	13,055	13,092
	Replacement costs	28,645	26,302	25,260
	Veterinary and AI	11,477	10,544	10,130
	Contractor	10,145	10,522	10,647
	Labour	28,236	25,926	24,899
	Depreciation	14,754	13,669	13,191
	Interest	7,409	6,802	6,533
	Electricity	3,163	2,955	2,874
	Insurance	8,895	8,167	7,844
	Total Costs	**164,537**	**150,840**	**146,349**
Net profit (excl) labour*	Per farm	96,211	88,073	83,730
	Per hectare farmed	2,406	2,202	2,093
Net profit (excl) labour* (Sunk costs)	Per farm	96,211	86,380	81,291
	Per hectare farmed	2,406	2,160	2,032

3.2.9. Technology focus

Acknowledging there is still a requirement to further reduce surpluses of N in order improve air and water quality, the application of technologies such as improved soil fertility, precision chemical N application to grassland and replacing chemical N with biological N fixation will be essential. Investments in soil fertility will reduce the impact of reduced N fertiliser levels with a huge proportion of Irish soils being sub optimum in soil fertility. While there has been a substantial increase in the use of lime in 2022 and this is to be welcomed, there has been a decline in the use of P and K. Similarly, there is an increased focus on the introduction of white clover in perennial ryegrass swards. Recent research is showing that the inclusion of white clover in the swards will result in increased profitability (circa €300) (McClearn et al., 2020). Similarly the movement to Low Emissions Slurry Spreading (LESS) technologies results in reduced gaseous emissions and increased nitrogen retention for grass growth. While there has been considerable progress around the use of LESS at farm level, the investment in soil fertility has not been as positive and requires further investment while movement in the area of white clover is now creating significant interest at farm level.

4. €riN modelling approach

4.1. Methodology

4.1.1. Model description

Demand for grazed grass and grass silage largely determines the proportion of grass utilised in the models. €riN assigns monthly utilisation rates to grazed grass and applies a fixed proportion (e.g. 75%) to grass silage. The Moorepark Dairy Systems Model (MDSM; Shalloo *et al.,* 2004) quantifies grass demand based on the herd's dietary requirements and the nutritional value of forages and supplements. The nutritional module of this model requires data on milk yields, animal body weights, pregnancy rates, calving pattern, replacement rates, housing periods and supplementary feeding levels. O'Mara's (1996) net energy (NE) system computes the herd's energy demand in lactation feed units (UFL) and provides NE values for feeds in UFL. The NE system takes the NE supplied by concentrate supplements from the animals' NE demand to calculate the NE provided by forage. The model estimates NE from grazed grass by relating the length of grazing season to NE supplied by forage, and uses the housing period to compute NE from grass silage. Additional computations convert NE required from forages to DM. Aggregating the DM required from forage and concentrate feed estimates the total DM demand, which the MDSM multiplies by the N content of the diet to calculate an animal's intake of N. Nitrogen outputs are calculated from milk and cattle sales and the N content of these products.

The €riN model uses N intakes and N outputs from the MDSM to estimate N excretion and related N losses. €riN quantifies N excretion in sheds and paddocks based on the length of the housing and grazing periods. The model accounts for N excreted on passageways and on collecting yards, i.e. soiled water, and partitions N excretion between dung and urine. €riN calculates ammonia, nitrate and nitrous oxides losses from urine, dung, slurry, soiled water and fertiliser N by multiplying the N load with emission factors from empirical Irish research. Nitrate emission factors vary by soil drainage class and by season for nutrient applications in the form of urine and dirty water. Ammonia emission factors for urine, dung and slurry are sensitive to timing and storage facilities, and nitrous oxide loss factors depend on soil type. The model uses a dinitrogen to nitrous oxide loss ratio to estimate dinitrogen losses. Excess or surplus N not vulnerable to leaching, volatilization or denitrification returns to the soil N pool. €riN uses a mass flow approach to calculate the soil N balance, and computes a farm's N surplus as the difference between N imports and N exports.

4.1.2. Dairy farm characteristics

The baseline dairy farm covered 40 hectares and carried 110 livestock units. Stocking rate averaged 2.75 livestock units/hectare (ha). The farm was in permanent pasture and the average age of the sward was five years. Well-drained soils were the predominant drainage class on the farm. Soils were weakly acidic, i.e. pH 6.3, and in the recommended index for P and K, index three. The farm spread 15 kg P, 37 kg K, 150 kg lime and 250 kg fertiliser N/ha per year. On average, a hectare of grassland produced 13.7 t DM/ha per year. The herd utilized 85% of the grass grown and received concentrate feed at an average rate of 2.55 kg/cow per day (i.e. 932 kg/cow per year).

4.2. Scenario analysis

€riN ran four different stocking rate N scenarios; at each stocking three different chemical N application, rates were evaluated. The baseline scenario represents previous regulations using an annual N exertion rate of 85 kg N/cow (2.94 cows/ha) with the average cow producing 92 kg organic N. Scenario 1 (Table 10) represents present regulations (band 2) permitting a maximum average stocking rate of 250 kg organic N/ha using an annual N excretion rate of 92 kg N/cow (2.74 cows/ha). Scenario 2 shows the impact of a reduction of 20 kg organic N/ha (2.53 cows/ha), Scenario 3 shows the impact of a reduction of 30 kg organic N/ha (2.39 cows/ha). All scenarios were evaluated using

250, 225, 200 and 175 kg of chemical fertilizer/ha, using a 40 ha farm. The same cow genotype were used in all stocking scenarios and 100% of the slurry excreted was recycled.

4.3. *Results*

4.3.1. Feed and milk production

In Scenario 1, reducing chemical fertilizer by 10% (to 225 kg N/ha), 20% (to 200 kg N/ha) and 30% (to 175 kg N/ha) reduced grass production by 0.5, 0.8 and 1.2 t DM/ha, respectively; this corresponded to a requirement to import 166, 275 and 433 kg silage DM/cow. Reducing organic N per hectare by 20 kg (230 kg organic N/ha – Scenario 2) reduced milk production from the farm by 9% and resulted in a surplus of silage of 370, 241, 113 kg DM/cow for chemical N application rates of 250, 225 and 200 kg N/ha, respectively, with a deficit of 48 kg DM/cow at 175 kg N/ha. Reducing organic N per hectare by 30 kg (220 kg organic N/ha –Scenario 3) reduced milk production from the farm by 13.2% and resulted in a surplus of silage by 550, 400, 240 and 113 kg DM/cow for chemical N application rates of 250, 225, 200 and 175 kg/ha, respectively.

4.3.2. Nitrogen balances

In the baseline scenario (organic stocking rate to 271 kg/ha) N imports were 356 kg/ha, N exports were 106 kg/ha and N surplus was 250 kg/ha at the highest fertiliser N levels. Decreasing fertiliser N by 25, 50 and 75 kg/ha in this scenario increased feed N imports by 7, 18 and 26 kg N/ha, respectively. The net effect of the 10, 20 and 30% reduction in fertiliser N was to reduce the N surplus by 17, 32 and 49 kg N/ha, respectively.

Within scenario 1 there was an annual import of 334 kg N/ha, with an export of 99 kg N/ha in the form of milk and cattle sales, and there was an N surplus of 235 kg N/ha (Table 11). Lowering fertiliser N application from 250 to 225 kg N/ha increased the purchases of silage and concentrate nitrogen by 9 kg N/ha and had no effect on cattle purchases or N exports. These changes decreased annual N imports by 16 kg N/ha and resulted in a similar reduction in N balance/ha.

Lowering the stocking rate to 220 kg organic N/ha reduced N imports by 16 kg/ha, increased exports by 15 kg/ha (sold silage) resulting in a reduction of 31 kg/ha in N surplus. In this scenario reducing chemical N application helped to balance feed supply on farm and further reduce N balance/ha. However, even though the model produced and sold grass silage, it could be anticipated that this would not happen at farm level and that grass utilisation may reduce.

Table 10. Description of agricultural inputs and outputs for spring-calving grass-based dairy farms on 40 hectares of well-drained soil										
Scenario	**Stocking rate (kg organic N/ha)**	**Fertilizer N (kg N/ha)**	**Dairy cows (Average/yr)**	**0-1 year olds (Average/yr)**	**Grass yield (t DM/ha)**	**Concentrate feed (kg DM/cow)**	**Grass silage demand (kg DM/cow)**	**Silage imports (kg DM/cow)**	**Milk solids (kg /cow)**	**Milk yield (t/ha)**
Baseline: Influence of chemical N application rate on farm feed budget at a stocking rate of 271 kg organic N per hectare										
Baseline	271	250	115	9	13.8	944	1121	252	433	16.1
Baseline	271	225	115	9	13.4	966	1152	352	434	16.1
Baseline	271	200	115	9	12.9	993	1191	483	436	16.1
Baseline	271	175	115	9	12.5	1002	1203	617	436	16.1
Scenario 1: Influence of chemical N application rate on farm feed budget at a stocking rate of 250 kg organic N per hectare										
S1	250	250	107	9	13.7	932	1098	8	435	15.1
S1	250	225	107	9	13.2	932	1098	166	435	15.1
S1	250	200	107	9	12.9	932	1098	275	435	15.1
S1	250	175	107	9	12.5	936	1101	433	434	15.1
Scenario 2: Influence of chemical N application rate on farm feed budget at a stocking rate of 230 kg organic N per hectare										
S2	230	250	98	8	13.7	880	1055	-370	434	13.7
S2	230	225	98	8	13.2	910	1085	-241	434	13.7
S2	230	200	98	8	12.9	910	1093	-113	433	13.7
S2	230	175	98	8	12.4	914	1096	48	433	13.7
Scenario 3: Influence of chemical N application rate on farm feed budget at a stocking rate of 220 kg organic N per hectare										
S3	220	250	93	8	13.5	880	1011	-550	431	13.1
S3	220	225	93	8	13.0	880	1011	-400	431	13.1
S3	220	200	93	8	12.8	878	1098	-240	431	13.1
S3	220	175	93	8	12.2	875	1010	-80	431	13.1

Table 11. Annual nitrogen imports, exports and balances (kg N/ha) for spring-calving grass-based dairy farms varying in stocking rate and applying different levels of fertiliser nitrogen to a well-drained soil. A dairy farm's annual N imports consists of fertiliser N, concentrate feed, silage purchases and cattle purchases. Milk, cattle and silage sales make up a farm's annual N exports										
Scenario	**Stocking rate**	**Fertilizer N**	**Concentrate feed**	**Silage purchases**	**Cattle purchases**	**N imports**	**N in Milk sales**	**N in Cattle sales**	**N exports**	**N surplus**
Baseline: Influence of chemical N application rate on annual N balance at a stocking rate of 271 kg organic N per hectare										
Baseline	271	250	83	16	7	356	93	12	106	250
Baseline	271	225	84	22	7	339	94	12	106	233
Baseline	271	200	87	30	7	324	94	12	106	218
Baseline	271	175	87	38	7	307	94	12	106	201
Scenario 1: Influence of chemical N application rate on annual N balance at a stocking rate of 250 kg organic N per hectare										
S1	250	250	76	1	7	334	88	11	99	235
S1	250	225	76	10	7	318	88	11	99	219
S1	250	200	76	16	7	299	88	11	99	200
S1	250	175	76	25	7	283	88	11	99	184
Scenario 2: Influence of chemical N application rate on annual N balance at a stocking rate of 230 kg organic N per hectare										
S2	230	250	65	0	6	322	80	10	110	212
S2	230	225	68	0	6	299	80	10	103	196
S2	230	200	68	0	6	274	80	10	96	178
S2	230	175	68	3	6	252	80	10	90	162
Scenario 3: Influence of chemical N application rate on annual N balance at a stocking rate of 220 kg organic N per hectare										
S3	220	250	62	0	6	318	76	10	114	204
S3	220	225	62	0	6	292	76	10	105	187
S3	220	200	62	0	6	268	76	10	97	171
S3	220	175	63	0	6	244	76	10	90	154

4.3.3. Nitrate leaching

Approximately 20% of surplus N (48 kg N/ha/year) in Scenario 1 (Organic N of 250kg N/ha) was leached in the form of nitrate (Table 12). Approximately, 30 kg of this N loss originated from urine deposited in paddocks, 14 kg came from the application of fertiliser N and 4 kg came from slurry, atmospheric deposition and soiled water (Figure 5). The €riN model estimated a nitrate loss rate of approximately 28% for urine N and used a 5.6% loss rate for fertiliser N. The model predicted that spreading 10%, 20% and 30% less chemical fertiliser N, in S1, reduced nitrate-N loss by 2, 4 and 6 kg/ha (Table 13). Reducing stocking rate from 271 kg (Baseline) to 250 kg (S1) organic N/ha decreased nitrate-N loss by 3 kg/ha. At stocking rate of 250 (S1) kg organic N/ha, lowering fertilizer N by 25 kg/ha (10%) decreased nitrate leaching by 2 kg N/ha (Table 14). Reducing chemical fertilizer N by 50 kg/ha (20%) in this scenario reduced predicted nitrate loss by 4 kg N/ha.

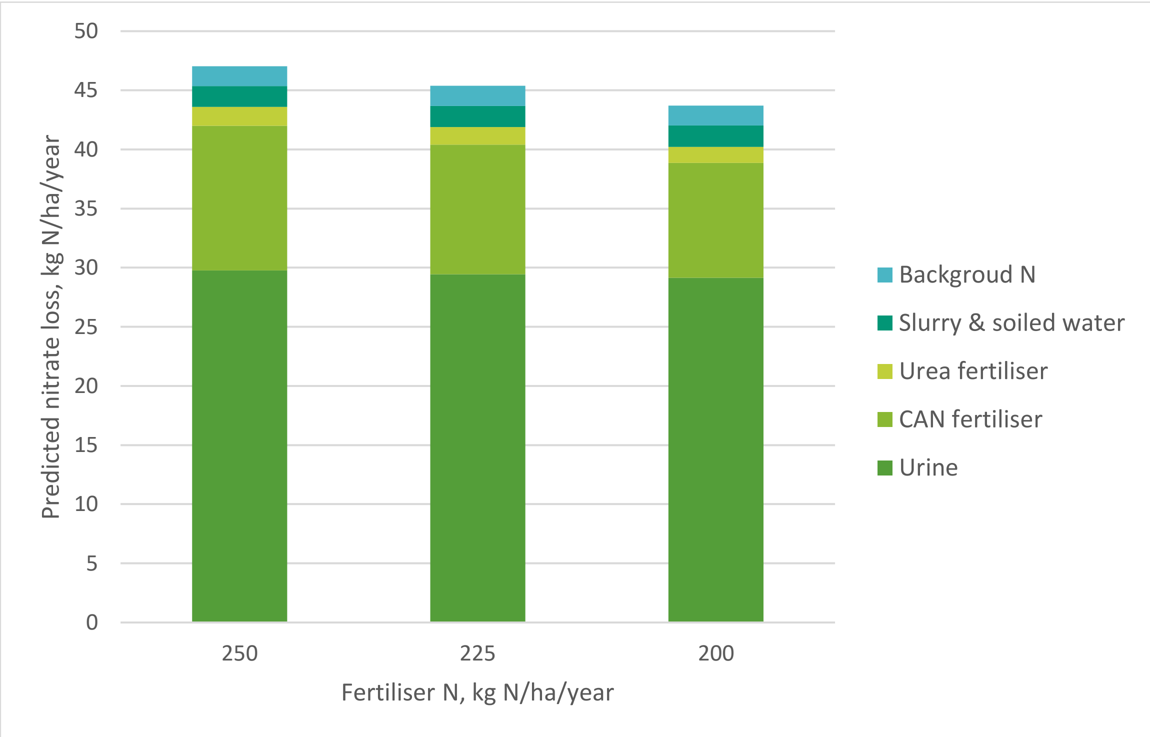


Figure 5. The impact of fertiliser N on predicted nitrate losses from a well-drained spring-calving grass-based dairy farm operated at a stocking rate of 250 kg organic N/ha

Table 12. Impact of chemical N fertiliser level on the organic N inputs and nitrate losses of spring-calving grass-based dairy farms stocked at 250 kg organic N/ha on a well-drained soil (kg N/ha per year)					
Fertilizer N	**Urine N**	**Dung N**	**Slurry N**	**Soiled water N**	**Nitrate leaching to 1 metre**
250	106	89	60	17	48
225	105	89	62	17	46
200	104	89	63	17	44
175	104	89	59	16	42

Table 13. Impact of stocking rate on the organic N inputs and the potential nitrate losses of well-drained spring-calving grass-based dairy farms spreading 250 kg fertiliser N/ha (kg N/ha per year)					
Stocking rate	**Urine N**	**Dung N**	**Slurry N**	**Soiled water N**	**Nitrate leaching to 1 metre**
271	113	95	68	18	51
250	106	89	60	17	48
230	100	82	51	15	45
220	91	77	42	14	44

Table 14. Potential influence of stocking rate and fertiliser nitrogen on the nitrogen losses of spring-calving dairy farms on a well-drained soil in kg N/ha per year							
Scenario	**Stocking rate**	**Fertilizer N**	**Nitrate leaching 1m**	**Ammonia emission**	**Dinitrogen**	**Nitrous oxide**	**N losses**
Baseline : Influence chemical N fertilisation on N use efficiency at a stocking rate of 271 kg N/ha							
Baseline	271	250	51	81	50	7	189
Baseline	271	225	49	80	49	7	185
Baseline	271	200	47	80	48	6	181
Baseline	271	175	45	80	47	6	179
Scenario 1: Influence chemical N fertilisation on N use efficiency at a stocking rate of 250 kg N/ha							
S1	250	250	48	75	49	7	179
S1	250	225	46	75	48	7	176
S1	250	200	44	74	47	6	171
S1	250	175	42	74	46	6	168
Scenario 2: Influence chemical N fertilisation on N use efficiency at a stocking rate of 230 kg N/ha							
S2	230	250	45	68	46	7	166
S2	230	225	44	68	45	6	163
S2	230	200	42	67	44	6	159
S2	230	175	40	66	43	6	155
Scenario 3 Influence chemical N fertilisation on N use efficiency at a stocking rate of 220 kg N/ha							
S3	220	250	44	64	44	6	159
S3	220	225	42	64	43	6	155
S3	220	200	41	63	43	6	153
S3	220	175	39	63	42	6	149

4.3.4. Gaseous N emissions

The majority (73-75%) of predicted environmental N losses from dairy farms (Table 14) occurred as gases. Ammonia constituted the bulk of predicted gaseous N emissions (58-59%), followed by dinitrogen (36-38%) and nitrous oxide (4-5%). Regardless of stocking rate or fertiliser N level, most of the potential ammonia losses came from slurry spreading (26-28%), and manure excreted onto shed floors, yards, fields and passageways (58-62%). Urine deposited on pasture explained the majority of dinitrogen emissions (79-86%) in all scenarios and contributed to nitrous oxide losses (23-28%). The rest of this gas originated from atmospheric N deposition (28-38%), fertiliser N (23-29%) and slurry N (12-16%).

Within stocking rate, dropping fertiliser N from 250 to 225 kg N/ha lowered predicted gaseous N emissions by 0.5-1% (1-1.4 kg N/ha) and reducing chemical fertiliser N to 200 kg N/ha decreased gaseous losses by 2-2.5%. These management changes reduced nitrous oxide by 2-6% (0.2-0.4 kg N/ha), and had a similar effect on ammonia and dinitrogen losses, mitigating both by about 0.6-1.2 kg N/ha. Increasing stocking rate caused an increase in predicted gaseous N losses analogous to surplus N. The influence of reducing chemical fertiliser N on potential gaseous N emissions tended to decline on a relative and absolute basis as stocking rate increased.

5. Organic N excretion rates for dairy cows

5.1. Background

DAFM introduced organic N excretion banding as part of the nitrates derogation application in 2022. This will come into effect in January 2023. The bands included are Band 1 <4,500 kg milk/cow, Band 2 4,501 - 6,500 kg milk/cow and band 3 >6,500 kg milk/cow. Band 1, 2 and 3 correspond to an organic N per cow figure of 80 kg N/cow, 92 kg N/cow and 106 kg N/cow. Full details of the bands, etc. can be found in 2021 https://www.teagasc.ie/media/website/publications/2021/Nitrates-Modelling-Final.pdf . The Teagasc National Farm Survey and ICBF databases were used to generate the milk production and milk solids concentrations, number of herds, and the concentrate feed levels in each bands. Average milk yields, milk fat and protein concentrations and concentrate feeding levels were generated for each band from the database. Table 15 shows the base assumptions dependent on the band for each year from 2015 to 2021. Over the 5-year period between 2015 and 2019 the average milk yield per cow, fat %, protein % and concentrate fed per were:

- 3,668 kg milk/cow, 4.08% fat, 3.47% protein and 750 kg of concentrate DM fed per cow for Band 1;
- 5,468 kg milk/cow, 4.12% fat, 3.50% protein, 949 kg of concentrate DM fed per cow for Band 2;
- 7,155 kg milk/cow, 4.04% fat, 3.46% protein and 1,423 kg of concentrate DM fed per cow for Band 3.

In 2015, Band 1 represented 15% and 25% of the milk produced and suppliers, respectively, and by 2021 that was 6% and 15%, respectively. In 2015, Band 2 represented 72% and 66% of the milk produced and suppliers, respectively, and by 2021 that was 66% and 66%, respectively. In 2015, Band 3 represented 13% and 9% of the milk produced and suppliers, respectively, and by 2021 that was 26% and 19%, respectively.

Of the herds that have milk yields greater than 6,500 kg/cow, just over 37% had milk yields under 6,800 kg/cow and 52% had milk yields under 7,000 kg/cow in 2020 with the corresponding figures for 2021 being 36% and 62%, respectively. This suggests that some of those farmers may have scope to reduce milk sales to come under the 6,500 kg band.

Table 15. Base assumptions included in the development of organic N excretion bands based on an average of 2015 to 2021							
		Representation					
Milk Yield bands		Supplier %	Milk %	Milk yield kg	Milk fat %	Milk protein %	Concentrate Kg DM
<4,500	2015	25	15	3,797	4.0	3.47	711
	2016	30	17	3,717	4.04	3.42	703
	2017	23	12	3,697	4.02	3.44	751
	2018	24	12	3,671	4.05	3.44	948
	2019	18	8	3,687	4.11	3.50	739
	2020	18	8	3,561	4.13	3.51	730
	2021	15	6	3,548	4.19	3.51	666
4,501-6,500	2015	66	72	5,379	4.02	3.50	807
	2016	63	71	5,336	4.10	3.46	820
	2017	66	71	5,431	4.08	3.48	905
	2018	63	67	5,469	4.12	3.47	1,215
	2019	67	68	5,523	4.15	3.53	980
	2020	65	68	5,540	4.18	3.54	953
	2021	66	68	5,599	4.21	3.53	966
<6,501	2015	9	13	7,144	3.93	3.43	1,285
	2016	7	12	7,127	4.01	3.41	1,324
	2017	11	17	7,155	3.99	3.44	1,381
	2018	13	22	7,186	4.06	3.44	1,724
	2019	15	24	7,162	4.08	3.49	1,445
	2020	16	25	7,109	4.11	3.50	1,399
	2021	19	26	7,017	4.13	3.49	1,402

Source: ICBF and NFS

5.2 The economic consequences associated with the introduction of banding

Banding was introduced by DAFM based on a request from the EU commission to link milk yield to organic N output. The economic impact of the introduction of banding for the higher milk yield categories (Band 3) was modelled to determine its impact on farm profitability. It is important to consider that the introduction of banding and increased organic N load for higher milk yield cows is only relevant where this drives the farm overall stocking rate over 250 kg organic N per hectare. It will also bring some new farmers into a derogation. The average stocking rates observed for the farmers in Band 3 would suggest that the majority will not have an organic N over 250 kg/ha. However, this is not always the case. In order to understand what the implications are for farmers that are operating at the higher level of organic N output per hectare, a scenario was created with a 40 ha farm operating at a current organic N output of either 236 or 245 kg organic N/ha across two scenarios where heifers were reared on and off the farm. Because the milk yield is well above the 6,500 kg cut off it would not be feasible for this herd to reduce milk yield under 6,500 kg/cow. It is important to note that if this herd was closer to the 6,500 kg/cow, the scenario that would be least financially damaging would be to reduce supplement feeding levels in order to reduce the herd average milk yields under 6,500 kg/cow. The analysis was completed based on 2021 costs and prices across a number of scenarios:

1. Farm organic N 236 kg/ha (based on an organic N of 92 kg/cow) and the heifers reared on the farm (replacement rate 25%).
2. Farm organic N of 236 kg/ha (based on an organic N of 92 kg/cow) with no heifers on the farm.
3. Farm organic N 245 kg/ha (based on an organic N of 92 kg/cow) and the heifers reared on the farm (replacement rate 25%).

4. Farm organic N of 245 kg/ha (based on an organic N of 92 kg/cow) with no heifers off the farm.

For all scenarios a number of strategies were evaluated when an organic N figure of 106 kg/cow was included to reduce the overall farm stocking rate to 250 kg of organic N/ha:

1. Reduced replacement rate.
2. Exportation of slurry – (It is important to note that exporting slurry involves exporting very valuable nutrients that will have a very negative impact on farm performance and would not be recommended).
3. Renting additional land (Land rented for compliance only – No effect on farm system).
4. Reducing cow numbers.

Where the farm was stocked at 236 kg organic N/ha and where the heifers were reared on the farm, the organic N went to 265 kg organic N/ha when the cows were reclassified as 106 kg organic N/ha (Table 16). In order to reduce the farm organic N to 250 kg/ha, the farm replacement rate would have to be reduced to 16% from 25%, or 57% of the slurry produced in a 16 week period would have to be exported, or 2.5 ha would have to be secured (if possible) or herd size would have to be reduced by 5.0 cows. While reducing the replacement rate would increase profitability (this is limited to what is biologically possible), all of the other interventions on the farm would be expected to reduce the profitability. Exporting 57% of the cow slurry will reduce profitability by €4,710 for the 40 ha farm, while renting in additional land will reduce profitability by €1,225, €1,838 and €2,450 for the 40 ha farm at a land rental cost of €500, €750 and €1,000/ha per year. Reducing cow numbers by 5 would be expected to reduce farm profitability by €4,900 assuming fixed costs are not sunk or €5,839 where fixed costs are sunk. In all of this analysis the models were run to bring the stocking rates down to 250 kg of organic N. At farm level getting to exact numbers will be more difficult. For example, renting an exact amount of land might be impossible leading to farmer renting more land than necessary to reach the 250 kg org N/ha.

Where the farm was stocked at 245 kg organic N/ha and where the heifers were reared on the farm the organic N went to 276 kg organic N/ha when the cows were reclassified as 106 kg organic N (Table 17). In order to get the farm organic N stocking rate down to 250 kg organic N/ha, the maximum replacement rate that could be carried is 10.5% (not biologically possible), or 92% of the slurry produced in a 16 week period would have to be exported, or 4.1 ha would have to be rented or cow numbers would have to be reduced by 9 cows. Exporting 92% of the cow slurry will reduce profitability by €7,826 for the 40 ha farm while renting in additional land will reduce profitability by €2,050, €3,075 and €4,100 at a land rental cost of €500, €750 and €1,000/ha per year, respectively. Reducing herd size by 9 cows would be expected to reduce farm profitability by €8,820, assuming fixed costs are not sunk or €10,512 where fixed costs are sunk.

Where the farm was stocked at 236 kg organic N/ha and where the heifers were reared off the farm the organic N went to 272 kg organic N/ha when the cows were reclassified as 106 kg organic N (Table 18). In order to get the farm organic N stocking rate down to 250 kg organic N/ha, 67% of the slurry produced in a 16 week period would have to be exported, or 3.5 ha would have to be rented or herd size would have to be reduced by 9 cows. Exporting 67% of the slurry will reduce profitability by €6,713 for the 40 ha farm while renting in additional land will reduce profitability by €1,725, €2,588 and €3,450 at a land rental cost of €500, €750 and €1,000/ha per year, respectively. Reducing herd size by 9 cows would be expected to reduce farm profitability by €8,820 assuming fixed costs are not sunk or €10,512 where fixed costs are sunk.

Table 16. Shows the impact of reducing replacement rate, exporting slurry, renting additional land or reducing cow numbers when organic N/cow increase from 92 kg to 106 kg while complying to maximum organic N/ha over the total farm at 250.				
	Number	**Organic N**	**Total Organic N**	**Organic N /Ha**
Band 2: 92 kg of organic N				
Cows	84	92	7728	
Replacement units	21	81	1701	
Total			9429	236
Band 3: 106 kg of organic N				
Cows	84	106	8904	
Replacement units	21	81	1701	
Total			10,605	265
Band 3: 106 kg of organic N- Replacement rate reduced				
Cows	84	106	8904	
Replacement units	13.4	81	1,089	
Total			9,993	250
Band 3: 106 kg of organic N-Slurry exported				
Cows	84	106	8904	
Replacement units	21	24-57	1,701	
Slurry production	84	16*0.33*2.4	1,064	
Proportion exported		57%	605	
Total			10,000	250
Band 3: 106 kg of organic N- Land rented				
Cows	84	106	8904	
Replacement units	21	81	1701	
Land area required (ha)	42.5		10,605	250
Land rented (ha)	2.5			
Band 3: 106 kg of organic N- Cow numbers reduced				
Cows	79.2	106	8,395	
Replacement units	19.8	81	1,604	
Total			9,999	250
Cow number reduction	5.0			

Table 17. Shows the impact of reducing replacement rate, exporting slurry, renting additional land or reducing cow numbers when organic N/cow increase from 92 kg to 106 kg while complying to maximum organic N/ha over the total farm at 250.				
	Number	**Organic N**	**Total Organic N**	**Organic N /Ha**
Band 2: 92kg of organic N				
Cows	87.3	92	8032	
Replacement units	21.8	81	1768	
Total			9799	245
Band 3: 106 kg of organic N				
Cows	87.3	106	9,254	
Replacement units	21.8	81	1,768	
Total			11,022	276
Band 3: 106 kg of organic N – reduced replacement rate				
Cows	87.3	106	9,254	
Replacement heifer units	9.2 (10.5%)	24-57	742	
Total			9,996	250
Band 3: 106 kg of organic N- Slurry exported				
Cows	87.3	106	9,254	
Replacement units	21.8	81	1,768	
Slurry production	87.3	16*0.33*2.4	1,106	
Proportion exported		92%	1,018	
Total			10,000	250
Band 3: 106 kg of organic N- Land rented				
Cows	87.3	106	9,254	
Replacement units	21.8	81	1,768	
Land area required	44.1		11,022	250
Land area rented	4.1			
Band 3: 106 kg of organic N-Reduced cow numbers				
Cows	79.2	106	8,395	
Replacement units	19.8	81	1,604	
Total			9,999	250
Cow number reduction	9.0			

Table 18. Shows the impact of exporting slurry, renting additional land or reducing cow numbers when organic N/cow increase from 92 kg to 106 kg while complying to maximum organic N/ha over the total farm at 250.				
	Number	**Organic N**	**Total organic N**	**Organic N /Ha**
Band 2; 92kg of organic N				
Cows	102.5	92	9430	
Total			9430	236
Band 3: 106 kg of organic N				
Cows	102.5	106	10,865	
Total			10,605	272
Band 3: 106 kg of organic N- Slurry exported				
Cows	102.5	106	10,865	
Slurry production	102.5	16*0.33*2.4	1299	
Proportion exported		67%	870	
Total			9995	250
Band 3: 106 kg of organic N- Land rented				
Cows	102.5	106	10,865	
Land area required	43.5		10,865	250
Land area rented	3.5			
Band 3: 106 kg of organic N-Reduced cow numbers				
Cows	94.3	106	9,996	
Total			9,996	250
Cow number reduction	9.0			

Where the farm was stocked at 245 kg organic N/ha and where the heifers were reared off the farm the organic N went to 282 kg organic N/ha when the cows were reclassified as 106 kg organic N (Table 19). In order to get the farm organic N stocking rate down to 250 kg organic N/ha, 96% of the slurry produced in a 16 week period would have to be exported, 5.15 ha would have to be rented or herd size would have to be reduced by 13 cows. Exporting 96% of the slurry will reduce profitability by €9,921 for the 40 ha farm while renting in additional land will reduce profitability by €2,575, €3,863 and €5,150 at a land rental cost of €500, €750 and €1,000/ha per year, respectively. Reducing herd size by 13 cows would be expected to reduce farm profitability by €12,740 assuming fixed costs are not sunk or €15,184 where fixed costs are sunk.

Table 19. Shows the impact of exporting slurry, renting additional land or reducing cow numbers when organic N/cow increase from 92 kg to 106 kg while complying to maximum organic N/ha over the total farm at 250				
	Number	Organic N	Total organic N	Organic N/Ha
Band 2: 92kg of organic N				
Cows	106.5	92	9,798	
Total			9,798	245
Band 3: 106 kg of organic N				
Cows	106.5	106	11,289	
Total			11,289	282
Band 3: 106 kg of organic N -Slurry exported				
Cows	106.5	106	11,289	
Slurry production	106.5	16*0.33*2.4	1350	
Proportion exported		96%	1296	
Total			9993	250
Band 3: 106 kg of organic N- Land rented				
Cows	106.5	106	11,289	
Land area required	45.15		11,289	250
Land area rented	5.15			
Band 3: 106 kg of organic N- Reduced cow numbers				
Cows	94.3	106	9,996	
Total			9,996	250
Cow number reduction	13.0			

The financial implications of reducing organic N from 250 to 220 kg/ha for farms that are already at a stocking rate of close to 250 kg of organic N and herd N excretion rates of 106 kg are significant. In the four scenarios discussed above if the organic N limit was reduced to 220 kg of organic N per hectare the land area required to be rented would be 8.2 ha, 10.1 ha, 9.4 ha and 11.4 ha. Depending on whether this land was available and at what cost, this measure would have a significant impact on profitability. In the scenario where there was no other option other than reducing cows numbers, the herd size would have to reduce by 15, 18, 20 and 24 cows based on the scenarios discussed above. The reduction in profitability associated with these cow reductions would be €14,700, €17,640, €19,600 and €23,520 where fixed costs are not sunk. The corresponding figures where fixed costs are sunk are €17,520, €21,024, €23,360 and €28,032. The corresponding reduction in net profit per ha ranges from €438/ha to just over €700/ha (circa 29% reduction in profit).

6. Discussion

The competitive advantage of grass-based systems are based on maximising grass utilisation. Where stocking rate is not high enough to utilize the grass grown on a farm it will result in lower grass utilisation, lower grass quality and reduced animal performance. Reducing the maximum stocking rate from 250 kg N/ha to 220 kg N/ha may result in a move away from a pasture-based system in Ireland towards a European model of forage maize/high concentrate feeding system as some farmers may want to increase output while restricted with cow numbers. International experience has shown that these high input systems are more detrimental to the environment. Additionally, it will reduce grass utilisation on the most efficient Irish grassland farms.

It is anticipated that N losses from Irish derogated grassland farmers will reduce significantly over the coming years due to significant reductions in chemical N application rates (the Food Vision Dairy Group has agreed a target to reduce chemical N by 27 to 30% by 2030); changes to slurry management and soiled water storage; higher livestock N excretion rates plus banding and extended closed period for chemical fertiliser as outlined in the 5th Nitrate Action Programme. All such measures will reduce N surplus on Irish derogated grassland farms. In recent years, the uptake of grassland measurement through PastureBase Ireland has increased leading to an improvement in N use efficiency. In addition the new fertiliser advice provided from Teagasc now tailors recommendations based on the predicted grass growth conditions to reduce fertiliser rates or delay application during periods of restricted grass growth as a result of adverse weather. This precision fertiliser advice will help to reduce nitrate loss during periods of drought. While the reductions in chemical nitrogen associated with the Food Vision report and the 5th Nitrate Action Programme could result in reduced grass production it is possible through better soil fertility, increased use of clover, better grassland management practise and improved nitrogen management, that the impact of these reductions could be significantly reduced. In this report, it is estimated that these new regulations will result in a reduction of between 5.9 and 9.0 kg/ha of nitrate-N leached to one metre level on a grass-only based system.

These reductions in nitrate-N leaching will go some way to meet the nitrate-N reductions required at a catchment level identified by the EPA (WFD River Basin Management Plan – 3rd Cycle), to achieve a water quality standard of 2.6 mg N/l in the downstream estuary. Identified within that report, nitrate concentrations are greatest in rivers in the south and southeast where there is more intensive farming coupled with freely drained soils, reduced recharge volumes and large year-to-year climatic variation. Five catchments required no reduction in N leaching (Avoca, Corrib, Erne, Fergus, Moy), eight require reductions of under 3 kg N/ha annually (Blackwater, Deel, Dodder, Lee, Liffey, Maigue, Suir and Tolka) while four required reductions of greater than 3 kg N/ha annually (Bandon, Boyne, Nore, Slaney) when calculated across the full catchment areas. The range of reductions of N entering the water required from each hectare in the catchments ranged from 0 to 18.7 kg N/ha annually; the Slaney requiring the greatest. There was also a strong influence of tillage farming in this catchment and changes to the green cover requirements in the new nitrate regulations will further reduce nitrate loss from these areas. The reduction in N leached in a catchment is also influenced by the area used for agricultural purposes (the greater the area the greater the potential to mitigate N losses) and the area with critical source areas (the greater the area within critical source area the greater the requirement to reduce N losses/ha). For example, in the Blackwater catchment the required load reductions entering the water would be approximately 5.4 kg N/ha across the critical source areas only, while in the Slaney the reductions required would be 43 kg N/ha if all of the reductions are to be achieved within the critical source areas. This report has shown that policies that are being implemented or have been implemented will result in between 5.9 kg and 9 kg of reduced nitrate-N leached to one meter level driven by increased organic N per cow, reduced chemical N fertiliser levels (NAP plus Food Vision strategies) and reduced chemical N fertiliser in January. It should be noted that these reductions are for the free draining soils and that were at the maximum in terms of organic N before the new NAP were implemented, the savings will be less for farms that are not at these levels. While this report does not go on to stipulate the impact of the loss at one metre level on the loss to rivers as the lag time can be from months to decades, it can be anticipated that the reduced loss will have a significant impact and will contribute to reduced loads at the catchment levels over time. These measures require time for their actual impact to be determined.

7. Reference

Dillon, P., Shalloo, L., Ruelle, E., Delaby, L., Fenton, O., Crosson, P., Creighton, P., O'Donovan, M., Horan, B., Wall, D. (2020). Review of the influence of chemical nitrogen application rate, soil type and agroclimate location on grass production, feed budgets, nitrogen use efficiency, environmental impact and farm profitability.

Dillon, P., Shalloo, L., Ruelle, E., O Donovan M., Horan B., Delaby L., Richards K., Wall D., Spink J. and O Brien D. (2021). The Impact of Nitrogen Management Strategies within Grass Based Dairy

Systems. 2021 https://www.teagasc.ie/media/website/publications/2021/Nitrates-Modelling-Final.pdf

Di, H. J., and K. C. Cameron. (2002). Nitrate leaching in temperate agroecosystems: Sources, factors and mitigating strategies. *Nutr. Cycl. Agroecosyst.* **46:** 237–256.

EPA, Water Quality in Ireland 2022. Editors Wayne Trodd, Shane O'Boyle and Mary Gurrie 2022. ENVIRONMENTAL PROTECTION AGENCY An Ghníomhaireacht um Chaomhnú Comhshaoil PO Box 3000, Johnstown Castle, Co. Wexford, Ireland.

Fenton, O., Mellander, P.-E., Daly, K., Wall, D.P., Jahangir, M.M.R., Jordan, P., Hennessey, D., Huebsch, M., Blum, P., Vero, S., Richards, K.G. (2017). Integrated assessment of agricultural nutrient pressures and legacies in karst landscapes. *Agric. Ecosyst. Environ*. **239**: 246–256. https://doi.org/10.1016/j.agee.2017.01.014

Fenton, O., Schulte, R.P.O., Jordan, P., Lalor, S.T.J., Richards, K.G. (2011). Time lag: a methodology for the estimation of vertical and horizontal travel and flushing timescales to nitrate threshold concentrations in Irish aquifers. Environ. Sci. Policy 14, 419–431. https://doi.org/10.1016/j.envsci.2011.03.006

Hanrahan L., McHugh N., Hennessy T., Moran B., Kearney R., Wallace M. and Shalloo L. (2018). Factors associated with Profitability in pasture based systems of milk production. *Journal of Dairy Science,* **101**: 5474-5485.

Huebsch, M., Horan, B., Blum, P., Richards, K.G., Grant, J., Fenton, O. (2013). Impact of agronomic practices of an intensive dairy farm on nitrogen concentrations in a karst aquifer in Ireland. *Agric. Ecosyst. Environ*. **179**: 187–199. ttps://doi.org/10.1016/j.agee.2013.08.021.

Jordan, P., Melland, A.R., Mellander, P.-E., Shortle, G., Wall, D. (2012). The seasonality of phosphorus transfers from land to water: Implications for trophic impacts and policy evaluation. *Sci. Total Environ*. **434**: 101–109. https://doi.org/10.1016/j.scitotenv.2011.12.070.

Kim, H., Surdyk, N., Møller, I., Graversgaard, M., Blicher-Mathiesen, G., Henriot, A., Dalgaard, T., Hansen, B. (2020). Lag Time as an Indicator of the Link between Agricultural Pressure and Drinking Water Quality State. *Water,* **12**: 2385. https://doi.org/10.3390/w12092385.

McCarthy, J., Delaby, L., Hennessy, D., McCarthy, B., Ryan, W., Pierce, K.M., Brennan, A., Horan, B. (2015). The effect of stocking rate on soil solution nitrate concentrations beneath a free-draining dairy production system in Ireland. *J. Dairy Sci.* **98**: 4211–4224. https://doi.org/10.3168/jds.2014-8693.

McCarthy B., Pierce K., Delaby L., Brennan A. and Horan B. (2011). The effect of stocking rate and calving date on milk production of Holstein–Friesian dairy cows. *Livestock Science*, **153**, issue 1-3: 123-134.

McCarthy B., Pierce K., Delaby L., Brennan A. and Horan B. (2012). The effect of stocking rate and calving date on reproductive performance, body state, and metabolic and health parameters of Holstein-Friesian dairy cows. *Journal of Dairy Science,* **95**:3; 1337-1348.

McClearn B., Shalloo L., Gilliland T.J., Coughlan F. and McCarthy B. (2020). An economic comparison of pasture-based production systems differing in sward type and cow genotype. *Journal of Dairy Science*, **103:** 5445-4465.

McAleer E., Coxon C., Mellander P-E., Grant J. and Richards K. (2022). Patterns and drivers of groundwater and stream nitrate concentrations in intensively managed agricultural catchments. 2022. *Water,* **14**: 1388. //doi.org/10.3390/w14091388.

McAleer, E.B., Coxon, C.E., Richards, K.G., Jahangir, M.M.R., Grant, J., Mellander, Per.E. (2017). Groundwater nitrate reduction versus dissolved gas production: A tale of two catchments. *Sci. Total Environ.* 586: 372–389. https://doi.org/10.1016/j.scitotenv.2016.11.083.

Melland, A.R., Fenton, O., Jordan, P. (2018). Effects of agricultural land management changes on surface water quality: A review of meso-scale catchment research. *Environ. Sci. Policy*, 84, 19–25. https://doi.org/10.1016/j.envsci.2018.02.011.

Mellander, P.-E., Jordan, P. (2021). Charting a perfect storm of water quality pressures. *Sci. Total Environ*. **787**: 147576. https://doi.org/10.1016/j.scitotenv.2021.147576.

Mellander, P.-E., Jordan, P., Bechmann, M., Fovet, O., Shore, M.M., McDonald, N.T., Gascuel-Odoux, C. (2018). Integrated climate-chemical indicators of diffuse pollution from land to water. *Sci. Rep*. **8:** 944. https://doi.org/10.1038/s41598-018-19143-1.

Mellander, P.-E., Lynch, M.B., Galloway, J., Žurovec, O., McCormack, M., O'Neill, M., Hawtree, D., Burgess, E. (2022). Benchmarking a decade of holistic agro-environmental studies within the Agricultural Catchments Programme. *Ir. J. Agric. Food Res*. https://doi.org/10.15212/ijafr-2020-0145.

Mellander, P.-E., Melland, A.R., Jordan, P., Wall, D.P., Murphy, P.N.C., Shortle, G. (2012). Quantifying nutrient transfer pathways in agricultural catchments using high temporal resolution data. *Environ. Sci. Policy,* Catchment Science and Policy Evaluation for Agriculture and Water Quality, **24**: 44–57. https://doi.org/10.1016/j.envsci.2012.06.004.

Mellander, P.-E., Melland, A.R., Murphy, P.N.C., Wall, D.P., Shortle, G., Jordan, P. (2014). Coupling of surface water and groundwater nitrate-N dynamics in two permeable agricultural catchments. *J. Agric. Sci.,* **152**: 107–124. https://doi.org/10.1017/S0021859614000021.

O Brien D., Moran B and Shalloo L. (2018). A national methodology to quantify the diet of a dairy cow. *Journal of Dairy Science,* **101**: 8595–8604.

O'Mara, F. (1996). A Net Energy System for Cattle and Sheep. Department of Animal Science and Production, Faculty of Agriculture, University College Dublin, Belfield, Dublin 4.

Quemada M., Lassaletta L., Jensen L.S., Godinot O., Brentrup F., Buckley C., Foray S., Hvid S.K., Oenem J., Richard K.G., Oenema O. (2020). Exploring nitrogen indicators of farm performance among farm types across several European case studies. *Agricultural Systems,* **177**: 102689

Richards K.G., Jahangir M.M.R., Drennan M., Lenehan J.J., Connolly J., Brophy C. and Carton O.T. (2015). Effect of an agri-environmental measure on nitrate leaching from a beef farming system in Ireland. *Agriculture, Ecosystems and the Environment,* **202**:17-24.

Ruelle, E.; Shalloo, L.; Wallace, M.; Delaby, L. (2015). Development and evaluation of the pasture-based herd dynamic milk (PBHDM) model for dairy systems. *European Journal of Agronomy,* **71**: 106-114.

Ruelle, E., Hennessy, D., & Delaby, L. (2018). Development of the Moorepark St Gilles grass growth model (MoSt GG model): A predictive model for grass growth for pasture based systems. *European Journal of Agronomy,* **99:** 80-91.

Roche J.R., Ledgard, S.F., Sprosen M.S., Lindsey S.B., Penno J.W., Horan, B., Macdonald, K.A. (2016). Increased stocking rate and associated strategic dry-off decision rules reduced the amount of nitrate-N leached under grazing. *Journal of Dairy Science,* **99:** 5916–5925.

Ryan, W., D. Hennessy, J. J. Murphy, T. M. Boland, and L. Shalloo. (2011). A model of nitrogen efficiency in contrasting grass based dairy systems. J. Dairy Science, **94**:1032–1044.

Shalloo, L., Dillon, P.G., Rath, M. and Wallace, M (2004). Description and Validation of the Moorepark Dairy System Model. *Journal of Dairy Science* **87**: 1945-1959.

Shore, M., Jordan, P., Melland, A.R., Mellander, P.-E., McDonald, N., Shortle, G. (2016). Incidental nutrient transfers: Assessing critical times in agricultural catchments using high-resolution data. *Sci. Total Environ.* **553**: 404–415. https://doi.org/10.1016/j.scitotenv.2016.02.085.

Treacy, M., J. Humphreys, K. McNamara, R. Browne, and C. J. Watson. (2008). Farm-gate nitrogen balances on intensive dairy farms in the south west of Ireland. Ir. J. Agric. Food Res. **47**:105–117

Wall, B., A. Cahalane, and J. Derham. (2020). Ireland environment—an integrated assessment 2020. Wexford (Ireland): Environmental Protection Agency; p. 460.w