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

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Table of Contents

List of Figures

List of Tables

List of Appendices

Executive Summary

1. The expansion in the dairy industry in recent years has resulted in an increase in land area allocated to dairy farming; at farm gate level the expansion has resulted in an increase in nitrogen (N) surplus, increases in N use efficiency and lower emissions of N per unit of production.
2. A review of six large-scale dairy cow grazing experiments in the Republic of Ireland predicted that the rate of N which gave the maximum percentage change in stock carrying capacity was approximately 300 kg N/ha on both freely and imperfectly drained soils.
3. A clay loam soil type produced approximately 1,000 kg dry matter (DM)/ha more pastures than a sandy loam soil type, while the agroclimatic conditions at Moorepark produced 270 kg DM/ha more pasture than Ballyhaise; soil type and agroclimatic location had only small impacts on responses to N application rate.
4. Reducing N application rate from 250 to 200 kg/ha at a stocking rate of 2.5 cows/ha reduced the feed available on the farm from a surplus of 119 kg DM/ha to a deficit of 433 kg DM/ha. No cognisance was taken on the effect of reduced N fertilisation on grass chemical composition.
5. N surplus increases with increased N fertilizer application and increased stocking rate, which increases the risk of N loss; however water quality responses in groundwater and surface water are influenced by both static (e.g. soil, subsoil and bedrock type) and dynamic factors (e.g. climate, soil moisture deficit, depth to water table), which are spatially and temporally variable across the farming landscape. 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.
6. The economic impact on a 40 ha dairy farm of reducing N application rate by 25 and 50 kg N/ha in a fixed cow scenario when using 250 kg N/ha reduced farm profitability by €4,622 (5%) and €8,951 (10%), respectively. The GHG marginal abatement costs are large when the reduced grass DM production is replaced with imported feed onto the farm. Incorporating white clover into existing pastures and use of N use efficiency technologies has the potential to reduce these negative economic impacts.
7. Reducing N application rate by 20% on suckler beef farms reduced gross margin per hectare by 7% and net margin by 12%. Reducing N application rate by 22% on low land sheep farms reduced lamb output per hectare by 15% and net margin per hectare by 16%. Technology can help to alleviate these reductions.
8. Greater use of low emission slurry spreading technology, protected urea, increased soil fertility (including soil pH) and greater precision in grazing management have the potential to reduce N required for a given level of grass growth which would reduce N emissions.
9. Research has shown that incorporating white clover into grassland reduces requirement for chemical N by up to 100 kg N/ha and increases animal performance. The adoption of this technology at farm level has been very limited; it will require a number of years before there are sufficient uptake to replace significant levels of chemical N fertilizer. A considerable knowledge transfer and a continued research programme are required to get significant adoption.
10. Grass-based systems are focused on maximising grass production and utilisation and minimising the amount of feed imported onto the farm. This is both more profitable and more environmentally sustainable. A move to lower grass production carries the risk of greater importation of feed onto the farm which will lead to reduced profitability and a deterioration in environmental sustainability as has been demonstrated around the world.

Glossary of Terms

C	Carbon
CH_4	Methane
CO_2	Carbon Dioxide
CSO	Central Statistical Office
DM	Dry Matter
EPA	Environmental Protection Agency (Ireland)
FPCM	Fat and protein corrected milk yield
GHG	Greenhouse Gas
LU	Livestock Unit
MACC	Marginal Abatement Cost Curve
MoSt	Moorepark St Gilles Grass Growth Model
N	Nitrogen
NH_3	Ammonia
N_2O	Nitrous Oxide
NO_3^-	Nitrate
NO_2^-	Nitrite
NFS	National Farm Survey
NUE	Nitrogen Use Efficiency
NFS	National Farm Survey
P	Phosphorus
PBHDM Model	Pasture Based Herd Dynamic Milk Model
WFD	Water Framework Directive
TLPM	Teagasc Lamb Production Model

Introduction

Nitrogen (N) is essential for life and plays a key role in food production, being one of the most limiting factors together with water. That is why most farmers apply N fertiliser and animal manures to the land, to improve crop yield. In Ireland the use of N fertilisation has become an indispensable element of high animal performance from pasture based systems of production. Dairy systems rely on the seasonal production of pasture to produce milk. Compact spring calving synchronises animal demand with available pasture. This is supported by the application of chemical N to increase pasture production during the grazing season. The abolition of European Union (EU) milk quotas has resulted in a significant increase in dairy cow number, furthering the requirement for increase pasture production and chemical N application.

However, N losses contribute to climate change and lead to pollution of the environment. The EU Water Framework Directive (WFD) aims for at least 'good status' for all ground and surface waters. The Nitrates Directive is Ireland agricultural programme of measures to improve water quality. Ireland’s surface water quality compares reasonably with that in other EU countries, with 53% of surface water bodies meeting good or high ecological status compared to a European average of 40%. However, there has been a net decline in water quality since 2013. There is a continuing loss in high-status water bodies and numbers have fallen by a third since 2009. 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. This will require more appropriate management of N; N use efficiency will have to increase and N losses to the environment will have to reduce.

The objective of the current report is to investigate the influence of N fertiliser application rate on grass production, stock carrying capacity, N surplus and farm profitability on both sandy loam and clay loam soil texture classes in two agro-climatic regions. Additionally, it outlines new strategies to increase N use efficiency and reduce fertiliser N application rates on grassland.

1. The influence of N application rate, soil texture and agro-climatic region on grass production, the dairy herd feed budget, NUE and farm profitability

1.1 Background

The sustainability of the Irish grass-based sector is dependent on increased productivity and improved efficiency of the conversion of grazed pasture to animal products. Consequently the selection of improved animal genetics coupled with enhanced grazing management has the potential to yield further improvements in production efficiency. National statistics reveal clear evidence of increasing production efficiency within dairy farms in recent years through a combination of farm management practices allied to accelerated genetic improvement within the national herd. The removal of EU milk quotas has allowed the Irish dairy industry to significantly increase cow numbers and the land area under dairying.

FoodWise 2025 report declared its aspiration to increase the size of the agri-food sector. A guiding principal was that environmental protection and economic competitiveness would be considered as equal and complementary, one was not to be achieved at the expense of the other. The three pillars of sustainability - social, economic and environmental - are considered equally important, therefore as the sector grows it will be undertaken in the context of addressing environmental challenges. Currently Ireland faces significant challenges in meeting some national and international environmental targets with regards to greenhouse gas (GHG) emissions, air quality, biodiversity and water quality. The Teagasc Marginal Abatement Cost Curve (MACC) (Lanigan *et al.*, 2019) outlines 26 actions that farmers can use to reduce GHG emission levels by 10-15% by 2030 relative to 2017 levels. A new MACC for ammonia emissions was published in 2020 (Buckley *et al.*, 2020) and outlines 13 actions that farmers can use to reduce ammonia emission levels by 15.26 kt NH_3 by 2030. Many of the measures are similar to those in the GHG MACC. The European Green Deal announced by the European Commission in December 2019 has also identified an urgent requirement to reduce dependency on pesticides and antimicrobials, reduce excess fertilization, increase organic farming, improve animal welfare and reverse biodiversity decline in food production systems.

Grassland productivity is highly dependent on the supply of plant-available N from the soil. The N loss pathways of primary concern to society are nitrate (NO_3) leaching and emissions of GHGs and NH_3. The concentration of NO_3^- in water bodies in recent decades has been a cause of concern because of the potential threat to human health and because of the ecological and aesthetic consequences of eutrophication. The challenge is therefore to develop production systems with high NUE, low N surplus, a minimal environmental footprint and without detriment to the economic viability of the livestock enterprise.

The objective of the current report is to investigate the influence of N application rate on grass production, stock carrying capacity, N surplus, NUE and farm profitability on dairy farms on both sandy loam and clay loam soil texture classes in two agro-climatic regions using a modelling approach. The Moorepark St Gilles grass growth model (MoSt model; Ruelle *et al.*, 2018) was used to model the effect of N fertiliser application rate, soil type, and climatic conditions on grass growth and soil N dynamics. The Pasture-Based Herd Dynamic Milk Model (PBHDM model; Ruelle *et al.*, 2015) was used to estimate herd feed budgets and milk production. The Moorepark Dairy System Model (MDSM; Shalloo *et al.*, 2004) was used to evaluate the financial implications at farm level based on the outputs from the

PBHDM and the MoSt model. In addition, an analysis of the impacts of reducing N application rate on beef and sheep farms was undertaken.

2. Nitrogen and animal production in Ireland

2.1 Animal numbers and NUE

Figure 2.1 shows the trends in dairy cow numbers; beef cow numbers, total cow numbers and quantity of N used on Irish farms from 2000 to 2019. Total cow numbers increased by approximately 68,000 or 2.9% over the period. Beef cow numbers reduced by approximately 193,000 or 17%, while dairy cow numbers increased by approximately 260,000 or 22%. Over the period the use of N fertiliser has reduced by approximately 41,000 tonnes, however the use has been variable; lowest in the period 2007 to 2012 albeit with a peak in 2010 and similar in 2000 to 2003 and 2017 to 2019.

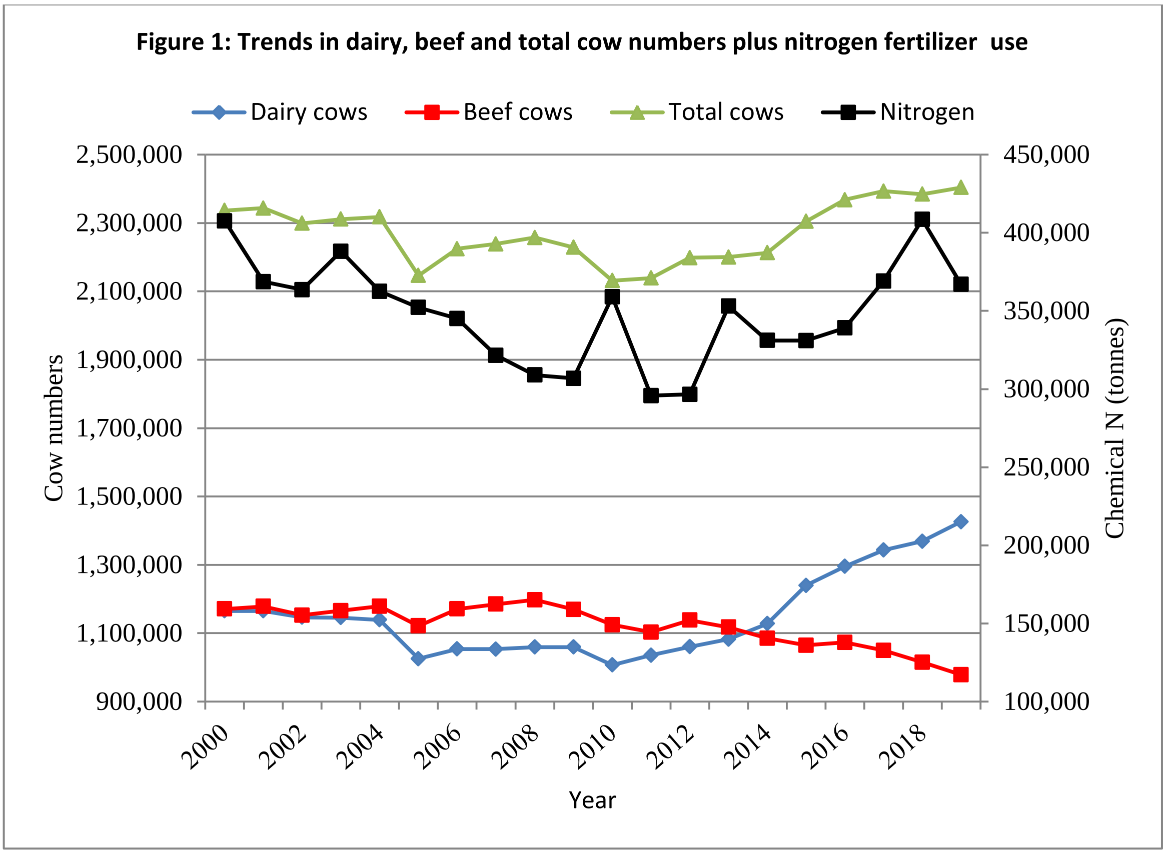

Figure 2.1 Trends in dairy, beef and total cow numbers plus chemical N use

Source: CSO

2.2 Trends in dairy farm productivity and sustainability

Table 2.1 shows the trends for a number of key physical characteristics using statistics from the Teagasc National Farm Survey (NFS), Central Statistical Office (CSO) and Irish Cattle Breeding Federation (ICBF) over the period 2010 to 2019. Over the nine year period, the number of specialist dairy farmers increased by 492 (15,654 to 16,146), area per dairy farm increased by 21% (50 to 61 ha) while dairy herd size increased by 40% (57 to 80 cows). Stocking rates increased by 13% (1.80 to 2.03 cows/ha) and level of chemical N fertiliser per hectare increased by 15% (161 to 185 kg/ha). Milk solids yield per cow increased by 17% (359 to 419 kg/cow) while calving interval reduced by 11 days, (401 to 390 days) and the 6-week calving rate increased by 13 percentage units (52 to 65%). The number of dairy cows increased by approximately 419,000, and milk deliveries to milk processors increased by 54%. Over the nine year period, grass utilisation increased from 6.7 to 8.0 t DM/ha. Outputs from the MoSt model suggest that the average grass growth response is 17 kg DM/ha per kg of N at an application rate of between 150 and 200 kg N/ha. Based on this grass growth response (also correcting for an increase in concentrate feed), the increase in chemical N in 2019 is only responsible for 31% of the increase in grass utilisation with the remainder coming from increased grassland management and utilisation when compared to 2010.

Table 2.1. Trends in dairy farm productivity 2010 to 2019										
	2010	***2011***	***2012***	***2013***	***2014***	***2015***	***2016***	***2017***	***2018***	***2019***
Dairy farm numbers	15,654	15,576	15,643	15,639	15,732	15,975	16,146	16,146	16,081	16,146
Area owned (ha)	40	45	45	45	45	45	45	45	47	47
Area total (ha)	50	57	58	58	58	58	58	59	61	61
Herd size-cows (no.)	57	66	68	68	70	70	74	76	79	80
Total livestock units (no.)	86	101	102	104	106	109	112	115	119	120
Stocking rate (cows/ha)	1.80	1.84	1.83	1.88	1.93	1.95	2.00	2.05	2.03	2.03
Concentrate fed per cow (kg)	959	862	1,011	1,159	954	905	935	1,030	1,354	1,144
Chemical N application rate (kg/ha)	161	154	150	173	169	159	167	172	184	185
Grazing season (days)	227	240	237	237	244	239	235	234	229	235
Somatic cell count ('000 cells/ml)	275	246	228	224	198	181	168	168	176	165
Calving Interval (days)	401	402	396	393	395	391	388	390	387	390
6-week calving rate (%)	52	53	55	59	57	57	59	64	64	65
Caving January-April (%)	79	75	80	81	82	82	83	83	84	84
Milk yield (l/cow)	4,980	4,996	4,755	4,830	4,799	5,044	4,942	5,233	5,316	5,446
Fat %	3.85	3.89	3.94	3.94	3.98	4.03	4.08	4.09	4.14	4.17
Protein %	3.37	3.37	3.36	3.39	3.43	3.50	3.46	3.48	3.48	3.53
Milk solids/cow (kg)	359	363	347	354	356	380	372	396	405	419
Cow numbers	1,006,900	1,035,600	1,060,300	1,082,500	1,127,700	1,239,900	1,295,200	1,343,300	1,369,100	1,425,800
Milk delivered to processors ('000,000 l)	5,173	5,377	5,233	5,423	5,649	6,395	6,654	7,263	7,576	7,980
Nitrogen surplus/ha (kg)	-	-	154	185	170	156	165	172	201	179
Grass utilised/ha	6.7	7.1	6.7	6.7	7.2	7.6	7.7	8.0	7.5	8.0

Source: Teagasc National Farm Survey 2010-2019

Table 2.2 shows a range of sustainability indicators for dairy farms over the period 2013 to 2019 on both per hectare and per kg of fat and protein corrected milk basis (Buckley and Donnellan, 2020). Both GHG and NH_3 emissions per kg of fat and protein corrected milk reduced however, emissions per hectare increased over this time period. Over the period 2013 to 2019 N surplus increased by 2.1/ha per year, NUE increased by 0.43% per year and kg of fat and protein corrected milk per kg of N surplus increased by 1.3 kg per year. The results include 2018 which was not a normal year due to the severe drought in the summer (>16 weeks without rainfall). If a three year rolling average was used, the increases in surplus would have been less and the increases in NUE would have been greater.

Table 2.2 Dairy farm sustainability indicators

	2013	*2014*	*2015*	*2016*	*2017*	*2018*	*2019*
GHG[1] emissions/kg FPCM[2] (kg CO_2 eqv)	1.31	1.24	1.14	1.13	1.14	1.19	1.14
Ag GHG emissions/ha (tonnes CO_2 eqv)	8.07	8.07	8.32	8.45	8.65	8.63	8.69
NH_3[3] emissions/kg FPCM (kg NH_3)	0.0065	0.0063	0.0059	0.0059	0.0059	0.0059	0.0058
NH_3 emissions/ha (kg NH_3)	44.1	44.3	45.6	47.1	47.8	48.8	49.0
Nitrogen (N) surplus/ha (kg)	185	170	156	165	172	201	179
N use efficiency (%)	19.7	22.2	25.0	24.0	24.4	21.5	24.4
Kg FPCM/kg of N surplus	59.2	66.1	78.6	75.3	76.0	63.6	73.7

[1]GHG = greenhouse gas; [2]FPCM = fat and protein corrected milk; [3]NH_3 = ammonia

Source: Teagasc National Farm Survey 2019 Sustainability Report

2.3 Relationship between chemical N application rate, stock carrying capacity

The optimum rate of N to apply for productive swards for grazing livestock is influenced by soil type, sward composition, stocking rate, grazing season length, management and livestock type used. Gately *et al.* (1984) reviewed the milk production results obtained from six large-scale grazing experiments in the Republic of Ireland. In these experiments, rates of N varied from 51 - 495 kg N/ha and stocking rates varied from 1.54 - 3.90 cows/ha, and these were evaluated on four free draining and two imperfectly drained soils. The effects of the N application rates were measured as the percentage change in stock-carrying capacity at a given level of output/animal. The optimum rate of N was approximately 300 kg/ha based on this review, on both the freely and imperfectly drained soils.

3. N loss to the environment

Nitrogen (N) is essential for life and plays a key role in food production, being among the most important crop yield-limiting factors in the world, together with water (Mueller *et al.*,2012). At the same time, N losses contribute to climate change and lead to environmental pollution as reactive nitrogen (Nr) is lost along the N cascade (Galloway *et al.*, 2008), which is harmful for the functioning of ecosystems and human health (Fowler *et al.*, 2013). Despite the positive effect of N fertiliser use on agricultural production (Whitehead, 1995), the efficiency with which N is used is variable (Watson and Atkinson, 1999). In the past 50 years, growth in demand for food has been met primarily by steady increases in agricultural productivity driven by an increasing reliance on chemical fertilisers and herbicides (Arneth *et al.*, 2019). Since 1961, global production of food (cereal crops) has increased by 240% (until 2017) because of land area expansion and increasing yields (IPCC, 2019). Continued productivity gains from these practices are now increasingly uncertain while antagonistic environmental impacts such as more intense competition for natural resources, increased GHG emissions, and further deforestation and land degradation are anticipated (FAO, 2017). Recent studies have suggested that current N losses from global agriculture to the environment are too high (Steffen *et al.*, 2015) and continuing population and consumption growth during the coming decades will further increase the demand for N fertiliser and increase N losses unless significant improvements are made in the whole food production–consumption chain (Godfray *et al.*, 2010; Sutton *et al.*, 2013; Mogollon *et al.*, 2018).

3.1 N loss pathways from grassland systems

As N moves within grassland systems, unavoidable losses occur through four major loss pathways: nitrate (NO_3^-) leaching, N_2O emissions, N_2 and ammonia (NH_3) volatilisation (Whitehead, 1995). Nitrate can also be converted to ammonium and lost to water on heavier textured soils. Grazing is accompanied by localised deposition of N in urine and dung patches, which can contribute to environmental N pollution either as NH_3 and N oxides in air or as NO_3^- and NO_2^- in soil and ground water (Tamminga, 1992). Nitrate is an extremely soluble form of N which does not bind with the surfaces of clay minerals nor does it form insoluble compounds with other elements that it encounters when moving through the soil. Because NO_3^- is soluble, it can readily move with soil water toward plant roots to be taken up by them. Nitrate leaching losses are problematic within grazing systems (Haynes and Williams, 1993; Ledgard *et al.*, 1999), as elevated N applications via urine deposition by grazing animals is poorly attenuated within the soil (Haynes and Williams, 1993; Decau *et al.*, 1997). During periods of high rainfall such as late autumn and winter, large amounts of water entering and passing through the soil carry NO_3^- beyond the soil root zone. Separately, NO_2^- is also produced naturally as part of the process of converting NH_3 into NO_3^-. Although NO_2^- moves in a similar manner to NO_3^- in soil and groundwater, it seldom accumulates in soil since the process of conversion from NO_2^- to NO_3^- is generally much faster than the conversion from NH_3 to NO_2^-. Finally, the concentration of NH_3 in the soil is also generally quite low (<1 mg/kg) because it is quickly converted to NO_3^- under conditions that are favourable for mineralization. The exception is where high rates of an ammonium fertiliser (anhydrous ammonia, urea or ammonium sulphate) or high rates of manure are applied and heavy rainfall washes this concentrated ammonium from the field into surface water.

In addition to NO_3^- leaching, losses of N also occur through NH_3 volatilization and denitrification. Ammonia volatilisation occurs when manure or NH_3-based fertilisers (particularly urea) are applied to the surface of the soil in dry conditions. While in excess of 50% of the ammonium N from manure can be lost to the air under warm, dry conditions, the concentrations of NH_3 released are not high enough to cause direct environmental or human health harm outdoors, and most is re-deposited within a few hundred metres of where it was released. Ammonia concentrations can accumulate to toxic levels in confined areas such as barns or manure storages. There are concerns that some of this NH_3 could contribute to the production of fine particulates, causing a decline in air quality and damage to sensitive ecosystems. Denitrification is a natural process where microbes in the rooting zone use the oxygen in NO_3^- where there is not enough air in the soil. This process converts the NO_3^- into gaseous forms of N - primarily N_2, but also into N_2O or nitric oxide (NO). Chemical N fertiliser is an important source of N_2O, a potent GHG, which accounts for 15% of total Irish agricultural emissions. Conditions that favour denitrification within the rooting zone are soils with slow internal drainage (fine textured soils), an ample carbon supply (food for the microbes) and saturated soils from shallow groundwater or heavy rainfall. Therefore different parts of the agricultural landscape depending on the soil, subsoil and bedrock combination have varied levels of natural attenuation capacity (i.e. denitrification capacity) (Clagnan *et al.*, 2018; Jahangir *et al.*, 2012)

3.2 Water Quality in Ireland

The EU WFD (OJEC, 2000) is a multi-part and multi-stage piece of legislation that aims to achieve at least "good" water quality in all EU water bodies. In Ireland, the Nitrates Directive (EC, 1991) implemented since 2007 is Ireland's agricultural programme of measures. This Directive places restrictions on all potential N inputs into a farming system including cattle stocking rates, organic and inorganic fertiliser rates, the time of spreading and their storage. Water quality monitoring and analysis in Ireland is undertaken by Environmental Protection Agency (EPA) which provides an evaluation of the ecological health of Ireland's rivers, lakes, canals, groundwater's, estuaries and coastal waters against the standards and objectives set out in the EU WFD and National River Basin Management Plan 2018-2021. The most recent assessment (EPA, 2019) is based on the assessment of biological and environmental data collected from 2,703 surface water bodies and from 514 groundwater bodies over the period 2013-2018. The report finds that 52.8% of surface water bodies assessed are in satisfactory ecological health being in either good or high ecological status compared with 55% for the last assessment period of 2010 – 2015, a decrease of 2.6% (Figure 3.1). The report also documents that coastal waters have the highest proportion of good or high ecological status (80%), followed by rivers (53%), lakes (50.5%) and estuaries (38%). In addition, 92% of groundwater bodies were found to be in good chemical and quantitative status, accounting for 98% of the country by area. This is a 1% improvement in the number of water bodies in good chemical and quantitative status when compared with the previous assessment (2010-2015). From a water quality perspective, the quality of Irish groundwater and surface waters is among the best in Europe. Under the WFD, the EPA reports show that overall levels of pollution remain relatively constant since the beginning of the 1990s. Some improvements have been made with the length of seriously polluted channel being reduced to just over 6 km in the 2013 - 2015 period compared with 17 km between 2010 and 2012 and 53 km between 2007 and 2009.

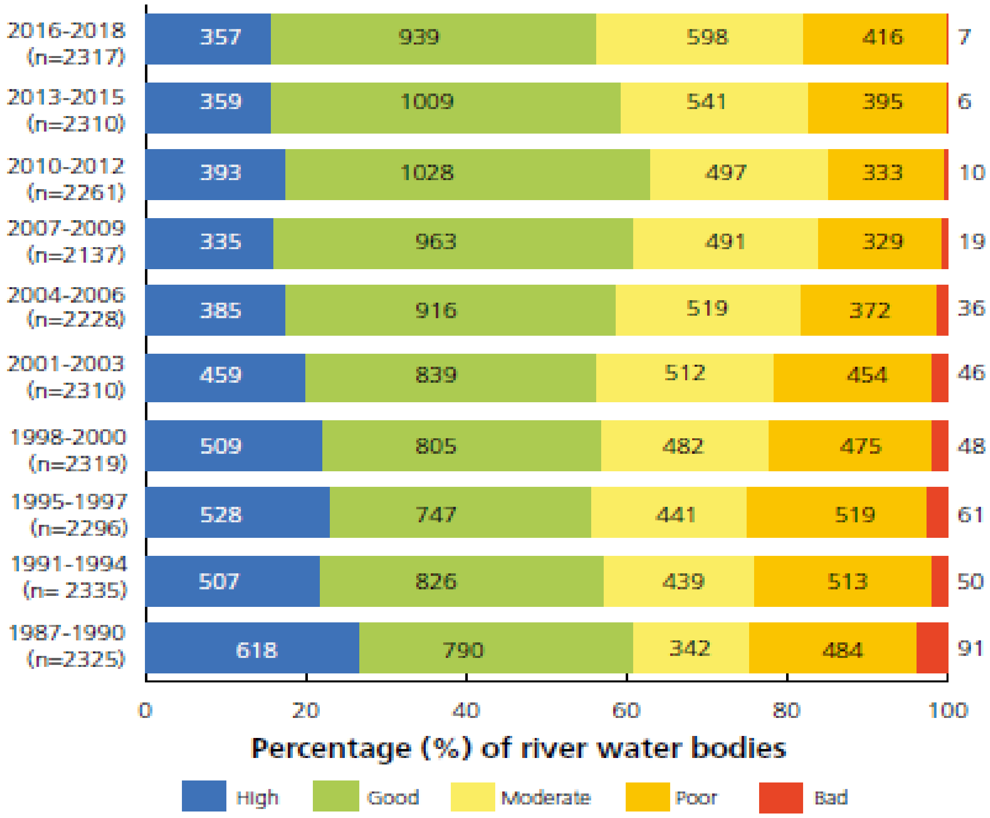

Figure 3.1 Trends in river water quality using the Q value system) from 1987 to 2018

Source: EPA, 2019

3.3 The role of sustainable grazing systems

Among dairy production systems, a grass-based model is peculiar in design, due to its high reliance on the natural forces of climate for the production of perishable feed and on animals for the autonomous management of feed quality and utilisation. The overall integrity of this model of milk production is based on highly productive grassland management and high production efficiency on a predominantly pasture-based diet over a prolonged grazing season. Such systems are uniquely a compromise between the dual objectives of maximising the utilisation of pasture and maintaining high animal intakes and performance, with minimal use of imported feed and fertiliser inputs.

Identifying the appropriate stocking rate (SR) is the key strategic decision for pasture-based dairy farms. This is generally defined as the number of animals allocated to an area of land (i.e. cows/ha). Although the beneficial impacts of SR on grazing system productivity have been widely reported, the impact of SR on environmental efficiency must also be considered. Previous studies have indicated that increased SR was associated with increased chemical fertiliser and supplementary feed importation, greater nutrient surpluses and reduced nutrient-use efficiency, resulting in increased losses to groundwater and the general environment. Both McCarthy *et al.* (2015) and Roche *et al.* (2016) investigated the direct effect of SR on NO_3^- leaching and both studies reported either stable or declining NO_3^- leaching with increasing SR; the critical proviso, however, was that strictly no additional N fertiliser or supplements were introduced at higher SRs.

In terms of relative agriculture pressures on water resources, the EU gross N and P balances provide an indication of the potential nutrient surpluses on agricultural land (kg N and P per ha per year) in different countries over time. The most recent analysis (2015) indicates that Ireland has a national N and P surplus of 42 kg N and 5 kg P/ha, respectively, which is below average for member states (Figure 3.2, Eurostat, 2019) and indicative of the comparatively extensive nature of Irish agriculture. The average N and P balance over the period 2016 to 2018 on Irish dairy farms was 179 and 12 kg/ha, respectively (Buckley and Donnellan, 2020).

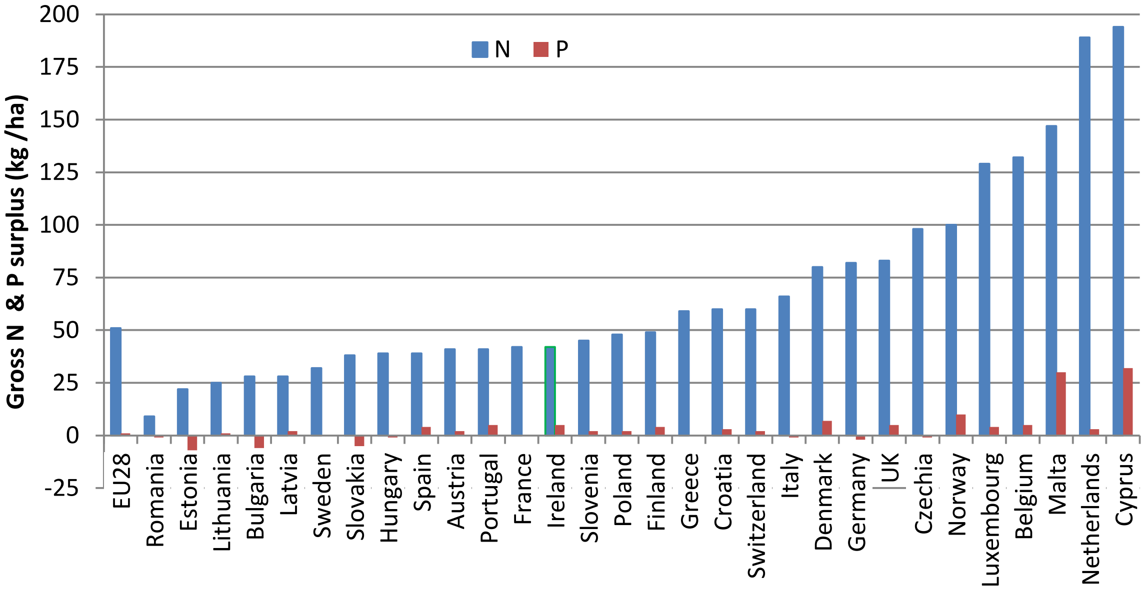

Figure 3.2 Nitrogen (N) and phosphorus (P) surplus for EU countries in 2015

Source: Eurostat, 2019

It is now also recognised that a number of changes to traditional management practices are required to maintain low levels of nutrient loss within intensive pasture-based systems including increased grazed pasture utilisation, adequate soil fertility and slurry management facilities on farm, greater use of organic manures to replace chemical fertiliser, more strategic use of available chemical N allowances, reduced cultivation at reseeding, improved grazing management and nutrient management planning, and, importantly, the preferential management of higher risk farm areas in February/September period. Indeed, in a recent 11 year analysis of grassland management practice and water quality on a risky free-draining site, Heubsch *et al.* (2013) observed low levels of N loss to groundwater within intensively managed dairy systems including an annual application of 250 kg/ha of chemical N fertiliser where the aforementioned management practices were applied.

4. Modelling the impact of N application rate, soil texture and agro-climatic region on grass production, dairy herd feed budget and on soil nitrogen dynamics

4.1 Models used

Both the Moorepark St Gilles Grass Growth model (MoSt model) (Ruelle *et al.*, 2018) and the Pasture Based Herd Dynamic Milk Model (PBHDM model) (Ruelle *et al.*, 2015) were used to model the effect of N application rate, stocking rate, soil texture, and agroclimatic region on grass growth, dairy herd feed budget and on soil N dynamics. The MoSt model is a dynamic model developed in C++ describing the grass growth and the nitrogen (N) and water fluxes of a paddock. The model is run with a daily time step simulating soil N mineralisation, immobilisation and water balance, grass growth, N uptake and grass N content. The model is driven by a daily potential growth depending on the solar radiation and the total green biomass. To calculate the actual daily growth, this potential growth is then multiplied by parameters depending on environmental conditions (temperature, water in the soil and radiation) and a parameter depending on the availability of the mineral N in the soil compared to the N demand associated with the potential grass growth. The PBHDM model comprises the herd dynamic milk model and integrates it with a grazing management and a paddock sub-model. Animal intake at grazing is dependent not only on the animal characteristics but also on grass availability and quality. It also depends on the interactions between the animal and the grass during the defoliation process. Management of grass on farm can be regulated through different rules during the grazing season including the decision to cut some paddocks in the case of a grass surplus and to allocate supplementation in the case of a grass deficit.

4.2 Soil texture and agro-climate region selected

A sandy loam (6% OM, 60% sand and 15% of clay soil depth of 100 cm) and clay loam (8% OM, 28% sand and 36% clay, soil depth of 100 cm) were used in the simulation. The sandy loam is representative of a Teagasc Moorepark type soil while the clay loam is representative of a Teagasc Solohead or Teagasc Grange type soil. Two agroclimatic regions were used for meteorological data; in the south Teagasc Moorepark (52°09'52.3"N 8°15'36.6"W) and in the north Teagasc Ballyhaise (54°03'01.3"N 7°18'40.3"W). Mean daily temperatures at Moorepark are higher (10.0 versus 9.3°C), annual rainfall very similar (1,014 mm versus 1,005 mm) and annual radiation hours higher (10,931 J/cm^2 versus 10,561 J/cm^2) compared to Ballyhaise (Appendix 10.1).

Based on the agroclimatic regions defined by Holden and Brereton (2004), the agroclimatic regions represented in the model capture over one-third of the agricultural soils (~ 35.6%). Overlay analysis of the indicative soil texture map with these agroclimatic regions indicates a distribution of 3.3% and 75.0% for coarse loamy and fine loamy, respectively. At national level this represents ~27.6% of the agricultural land area.

4.3 Simulation

Table 4.1 describes the main inputs used in the simulation. Farm size was fixed at 40 ha and included 40 paddocks. A total of 140 main scenarios were analysed in each simulation: 5 stocking rates (2.00, 2.25, 2.50, 2.75, and 3.00 cow/ha), 7 N application rates (0, 50, 100, 150, 200, 250 and 300 kg N/ha), two agroclimatic regions (Moorepark and Ballyhaise) and two soil textures (sandy loam and clay loam). Each scenario was simulated over 16 years using the climatic variables particular to that year across the two regions.

Table 4.1 Description of input parameters used in the simulations					
Farm size	40 ha divided into 40 paddocks				
Grass feeding value/kg DM	0.93 FV[1] 1.0 UFL, 100 PDI				
Silage feeding value/kg DM	1.1 FV, 0.78 UFL, 75 PDI				
Concentrate feeding value/kg DM	1.03 UFL, 120 PDI				
Grazing season	10 February to 20 November				
Grazing post-grazing residual	3.5 cm to 15 April; 4 cm thereafter				
Concentrate feeding	4 kg concentrate/day for the 5 first months of lactation; total concentrate fed - 600 kg/cow				
Slurry available nitrogen	Available slurry N - 15 kg N/cow, 60% organic, 40% mineral				
Slurry application	Spread in two applications: 75% on the 1 February; 25% on the 1 June				
Chemical N (kg/ha)	In 6 even applications[2] from 0 kg N/ha to 300 kg N/ha by steps of 50 kg N/ha				
Stocking rate (cow/ha)	2.00	2.25	2.50	2.75	3.00
Number of lactating animals	80	90	100	110	120

[1]UFL: "Unité Fourragère lait" 1 UFL =1,700 kcal of net energy for lactation (NEL); PDI: "Protéine Digestible dans l'intestin" , FV: Fill Value (Faverdin *et al.*, 2010, INRA, 2010)2 16th of February, 1st of April, 1st of May, 15th of July, 1st of August and 15th of September

4.4 Feeding and grazing management simulation

The model simulated good practices in terms of grassland, dairy cow nutrition and slurry management. Cows were supplemented with 4 kg concentrates (1.03 UFL, 120 PDI) per cow per day (3.6 kg DM) for the first five month of their lactation, irrespective of grass availability; total annual concentrate supplementation level was maintained at 600 kg per cow per lactation. The grazing season was from the 10th of February to 20th of November, irrespective of the amount of grass on the farm. While indoors the lactating cow was fed grass silage ad libitium (quality 1.1 FV, 0.78 UFL, 75 PDI); the dry cow was allocated 80% of ad libitum intake of the lactating cow (around 10 kg silage DM/cow per day). During the grazing season cows were housed when the soil saturation level was over 90%. Grazing management is driven by both pre- and post-grazing sward height, while farm grass cover is evaluated daily and is compared with herd requirement. In situations where farm grass cover is greater than target, some paddocks are allocated for silage conservation rather than grazed and vice versa if paddocks are closed for silage and grass supply is not adequate. In the case of a grass deficit, grass silage can be fed up to a rate of 6 kg DM/cow. In the simulations priority is given to grazing over silage conservation; if silage produced on the farm is not adequate it is purchased.

In the simulations, mineral N fertiliser was applied in 6 equal applications: 16th of February, 1st of April, 1st of May, 15th of July, 1st of August and 15 of September. Slurry was applied on the 1st of February (75%) and the 1st of June (25%). The amount of slurry available was of 30 kg N per cow per year (based on 10 kg N collected during the housing period and 5 kg N during milking), 40% was mineral N and 60% was organic N.

The MoSt Grass Growth Model (Ruelle *et al.*, 2018) simulated grass growth (kg DM/ha), the N response (kg DM/kg N applied) and the organic matter (%). The Pasture based Herd Dynamic Milk Model (Ruelle *et al.*, 2015) simulated the number of days at grazing, the number of days at grazing without 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), the milk, protein and fat produced (kg/cow and per ha), the amount of silage produced (kg/ha), and the yearly surplus or deficit of silage (kg/ha). All outputs were simulated per day and are then summarised by week, season, year or full simulation.

4.5 The impact of soil texture, agro-climatic region and N application rate on grass growth and N response

Table 4.2 shows the influence of soil texture, agroclimate region and N fertiliser application rate on grass growth and grass growth response to N. Appendix 10.2 shows the influence of soil texture, agroclimate region and N application rate on seasonal grass growth. Grass growth (kg DM/ha) were 9,420, 10,544, 11,576, 12,521, 13,378, 14,167 and 14,894 at N application rates of 0, 50, 100, 150, 200, 250, 300 kg/ha, respectively. The average response to N fertiliser (kg DM/kg N fertilizer applied) (based on the difference between two consecutive N fertiliser application rates) was 22, 21, 19, 17, 16, and 15 going from 0 to 50, 50 to 100, 100 to 150, 150 to 200, 200 to 250 and 250 to 300 kg N/ha, respectively. The response to fertiliser N was slightly greater in the sandy loam soils than the clay loam (18.4 versus 18.1 kg DM/kg N); agroclimatic region had no effect. Annual grass production on the clay loam soils was approximately 1,000 kg DM/ha greater than that on the sandy loam. There was a much larger effect of year on grass production on the sandy loam soils with the Moorepark meteorological conditions than in the other three scenarios. On average grass production with the Moorepark meteorological conditions was 270 kg DM/ha greater than with the Ballyhaise meteorological conditions.

4.6 The impact of soil texture, agro-climatic region and fertiliser N application rate on dairy herd feed budget

Tables 4.3, 4.4, 4.5 and 4.6 show the influence of N fertiliser application rate and stocking rate on feed budget on a sandy loam soil with Moorepark meteorological conditions, sandy loam soil with the Ballyhaise meteorological conditions, clay loam with the Moorepark meteorological conditions and clay loam soil with the Ballyhaise meteorological conditions, respectively. Appendix Tables 10.3, 10.4, 10.5 and 10.6 shows the influence of soil type, agroclimatic region and stocking rate on grass production, grazing days and feed budget using 100 kg N/ha,150 kg N/ha, 200 kg N/ha and 250 kg N/ha respectively. In the sandy loam soil with the Moorepark meteorological conditions scenario reducing N fertiliser application rate from 250 to 200 kg reduced grass production by 808 kg DM/ha, increased the number of days requiring silage supplementation by nine and resulted in a requirement to purchase 645 kg of silage DM/ha at a stocking rate of 2.5 cows/ha (Table 4.3). In the Ballyhaise meteorological conditions sandy loam soil scenario reducing N fertiliser application rate from 250 to 200 kg reduced grass production by 796 kg DM/ha, increased the number of days requiring silage supplementation by 12 and resulted in a requirement to purchase 741 kg of silage DM/ha at a stocking rate of 2.5 cows/ha (Table 4.4). In the Moorepark meteorological conditions clay loam soil scenario reducing N fertiliser application rate from 250 to 200 kg reduced grass production by 774 kg DM/ha, increased the number of days requiring silage supplementation by four and resulted in a requirement to have just about enough silage (at 250 k gN/ha there was a surplus of 521 kg DM/ha) at a stocking rate of 2.5 cows/ha (Table 4.5). In the Ballyhaise meteorological conditions clay loam soil scenario reducing N fertiliser application rate from 250 to 200 kg reduced grass production by 768 kg DM/ha, increased the number of days requiring silage supplementation by five and resulted in a requirement to purchase 455 kg DM/ha of silage (at 250 kg N/ha there was a surplus of 77kg DM/ha) at a stocking rate of 2.5 cows/ha (Table 4.6).

Table 4.2 Impact of soil texture, agroclimatic region and chemical N application rate on grass growth and N responses					
Soil texture	***Agroclimatic region***	***Nitrogen (kg/ha)***	***Grass growth (SD) (kg DM/ha)***		***Nitrogen response (kg DM/kg N)***
Sandy loam	Ballyhaise	0	8,868	(824)	
		50	9,988	(842)	22.4
		100	11,026	(862)	20.7
		150	11,973	(856)	18.9
		200	12,859	(879)	17.7
		250	13,660	(899)	16.0
		300	14,406	(921)	14.9
	Moorepark	0	8,887	(1,372)	
		50	9,991	(1,511)	22.1
		100	11,014	(1,576)	20.5
		150	12,003	(1,621)	19.8
		200	12,873	(1,697)	17.4
		250	13,674	(1,764)	16.0
		300	14,420	(1,857)	14.9
Clay loam	Ballyhaise	0	9,697	(897)	
		50	10,832	(869)	22.7
		100	11,875	(878)	20.9
		150	12,793	(894)	18.4
		200	13,626	(910)	16.7
		250	14,399	(937)	15.5
		300	15,101	(964)	14.0
	Moorepark	0	10,229	(823)	
		50	11,363	(823)	22.7
		100	12,387	(844)	20.5
		150	13,316	(865)	18.6
		200	14,154	(886)	16.8
		250	14,936	(919)	15.6
		300	15,648	(944)	14.2

Table 4.3 Influence of chemical N application rate and stocking rate on feed budget on a sandy loam soil with Ballyhaise meteorological conditions

Nitrogen (kg/ha)	*Stocking rate (cows/ha)*	*Grass growth (kg DM/ha)*	*Days without silage supplementation*	*Grass intake per cow (kg DM)*	*Silage intake per cow (kg DM)*	*Silage surplus/deficit (kg DM/ha)*
100	2.00	10,517	192	3,419	1,326	-382
100	2.25	10,771	177	3,330	1,409	-1,183
100	2.50	11,002	172	3,284	1,453	-1,980
100	2.75	11,279	162	3,220	1,508	-2,761
100	3.00	11,558	148	3,133	1,577	-3,552
150	2.00	11,548	207	3,507	1,241	367
150	2.25	11,762	192	3,420	1,321	-458
150	2.50	11,967	180	3,342	1,403	-1314
150	2.75	12,191	173	3,301	1,427	-2076
150	3.00	12,397	165	3,209	1,492	-2874
200	2.00	12,480	229	3,632	1,123	1057
200	2.25	12,681	212	3,539	1,208	227
200	2.50	12,868	194	3,451	1,301	-657
200	2.75	13,049	187	3,369	1,361	-1,470
200	3.00	13,218	176	3,272	1,424	-2,273
250	2.00	13,350	234	3,651	1,097	1,660
250	2.25	13,501	222	3,593	1,154	819
250	2.50	13,664	206	3,510	1,244	-84
250	2.75	13,814	194	3,409	1,318	-924
250	3.00	13,969	189	3,350	1,345	-1,685

Table 4.4. Influence of chemical N application rate and stocking rate on feed budget on a sandy loam soil with Moorepark meteorological conditions

Nitrogen (kg/ha)	*Stocking rate (cows/ha)*	*Grass growth (kg DM/ha)*	*Days without silage supplementation*	*Grass intake per cow (kg DM)*	*Silage intake per cow (kg DM)*	*Silage surplus/deficit (kg DM/ha)*
100	2.00	10,515	198	3,432	1,313	-334
100	2.25	10,759	178	3,307	1,427	-1,156
100	2.50	11,026	168	3,260	1,467	-1,931
100	2.75	11,270	160	3,196	1,515	-2,718
100	3.00	11,499	149	3,099	1,583	-3,505
150	2.00	11,560	213	3,529	1,221	417
150	2.25	11,786	194	3,415	1,332	-433
150	2.50	12,003	183	3,362	1,387	-1253
150	2.75	12,234	178	3,301	1,422	-2016
150	3.00	12,433	166	3,200	1,490	-2811
200	2.00	12,491	227	3,607	1,147	1,065
200	2.25	12,695	212	3,529	1,220	246
200	2.50	12,861	202	3,462	1,287	-608
200	2.75	13,062	187	3,359	1,368	-1,424
200	3.00	13,254	178	3,275	1,416	-2,196
250	2.00	13,355	233	3,634	1,119	1,663
250	2.25	13,510	219	3,571	1,180	807
250	2.50	13,669	211	3,527	1,227	-37
250	2.75	13,836	197	3,423	1,304	-857
250	3.00	14,000	189	3,343	1,347	-1,634

Table 4.5. Influence of chemical N application rate and stocking rate on feed budget on a clay loam soil with Ballyhaise meteorological conditions						
Nitrogen (kg/ha)	***Stocking rate (cows/ha)***	***Grass growth (kg DM/ha)***	***Days without silage supplementation***	***Grass intake per cow (kg DM)***	***Silage intake per cow (kg DM)***	***Silage surplus/deficit (kg DM/ha)***
100	2.00	11,536	187	2,745	1,924	77
100	2.25	11,709	183	2,712	1,953	-793
100	2.50	11,885	180	2,719	1,958	-1,658
100	2.75	12,057	177	2,688	1,970	-2,478
100	3.00	12,190	171	2,631	2,004	-3,332
150	2.00	12,507	190	2,767	1,903	737
150	2.25	12,660	185	2,738	1,931	-141
150	2.50	12,788	181	2,728	1,945	-1038
150	2.75	12,946	180	2,712	1,942	-1864
150	3.00	13,064	176	2,658	1,971	-2703
200	2.00	13,386	191	2,768	1,898	1,339
200	2.25	13,511	188	2,752	1,916	447
200	2.50	13,631	183	2,743	1,929	-455
200	2.75	13,759	182	2,724	1,934	-1,311
200	3.00	13,843	182	2,695	1,933	-2,137
250	2.00	14,196	191	2,773	1,897	1,878
250	2.25	14,301	189	2,778	1,896	984
250	2.50	14,399	188	2,778	1,899	77
250	2.75	14,496	185	2,746	1,912	-795
250	3.00	14,604	182	2,691	1,938	-1,646

Table 4.6. Influence of chemical N application rate and stocking rate on feed budget on a clay loam soil with Moorepark meteorological conditions

Nitrogen (kg/ha)	*Stocking rate (cows/ha)*	*Grass growth (kg DM/ha)*	*Days without silage supplementation*	*Grass intake per cow (kg DM)*	*Silage intake per cow (kg DM)*	*Silage surplus/deficit (kg DM/ha)*
100	2.00	12,035	198	2,944	1,745	479
100	2.25	12,217	192	2,909	1,778	-366
100	2.50	12,407	188	2,899	1,796	-1,220
100	2.75	12,570	184	2,877	1,799	-2,036
100	3.00	12,704	176	2,793	1,851	-2,868
150	2.00	13,015	203	2,978	1,713	1155
150	2.25	13,178	198	2,955	1,737	299
150	2.50	13,338	191	2,932	1,764	-570
150	2.75	13,439	186	2,872	1,798	-1442
150	3.00	13,607	182	2,822	1,820	-2236
200	2.00	13,907	202	2,969	1,723	1,756
200	2.25	14,030	201	2,964	1,720	896
200	2.50	14,159	194	2,952	1,745	-12
200	2.75	14,295	188	2,881	1,788	-854
200	3.00	14,379	184	2,837	1,797	-1,686
250	2.00	14,722	206	2,992	1,698	2,321
250	2.25	14,830	205	2,990	1,698	1,445
250	2.50	14,933	198	2,964	1,731	521
250	2.75	15,053	193	2,918	1,752	-319
250	3.00	15,141	186	2,863	1,784	-1,181

4.7 Nitrogen surplus and soil N water concentrations

The modelled N surpluses in Table 4.7 clearly indicate a linear reduction in N surplus with a reduction in N fertiliser inputs. Where stocking rate is maintained, the extra feed required for the dairy system was imported which has large implications on cost while also resulting in higher NUE at lower N fertiliser rates on the specific farm, however, the benefits are less clear if you include the land area used to grow the imported feed and the NUE associated with the imported feed production (Quemada *et al.*, 2020). Such individual scenarios can be placed in a wider context using nationally representative data from 150 specialist Irish dairy farms over a seven year period between 2006 and 2012 (Buckley *et al.*, 2016). That study period coincided with the introduction of EU Nitrates Directive regulations which aimed at minimising losses of N to the aquatic environment and results indicated that N surplus declined by 25.1 kg/ha from 180.4 to 155.3 kg/ha. This decline can almost entirely be attributed to reduced chemical N fertiliser inputs of 23.1 kg/ha. The most recent national farm survey report observed an average N surplus on dairy farms of 179 kg N/ha (Buckley and Donnellan, 2020).

Table 4.7. Surplus (kg N/ha) for 2, 2.5 and 3 livestock unit/ha (LU/ha) scenarios with corresponding chemical N inputs (accounting for imported feed, kg N/ha)

Location	Drainage	Fertilisation (kg N/ha)			
		150	**200**	**250**	**300**
		Surplus (kg N/ha) for 2 LU/ha			
Ballyhaise	Sandy loam	106	156	206	256
	Clay loam	107	157	207	257
Moorepark	Sandy loam	106	156	205	255
	Clay loam	107	157	207	257
		Surplus (kg N/ha) for 2.5 LU/ha			
Ballyhaise	Sandy loam	124	159	197	245
	Clay loam	119	157	197	247
Moorepark	Sandy loam	122	158	195	244
	Clay loam	108	146	196	246
		Surplus (kg N/ha) for 3.0 LU/ha			
Ballyhaise	Sandy loam	148	185	222	261
	Clay loam	145	183	223	262
Moorepark	Sandy loam	146	183	220	260
	Clay loam	135	173	212	251

Note: N surplus are calculated as N imports-N exports. N imports are the N from fertiliser, N from the concentrate and N from silage purchases. N exports are calculated as N from milk, N from meat export and N from silage sold. NUE is calculated as N export/N import. It should also be noted that for <200 kg N/ha scenarios purchasing feed/silage artificially increases NUE through externalisation of NUE associated with the production of the imported feed.

It is interesting to consider what happens to this N surplus and how it affects connected water bodies. Nutrient losses to ground and surface waters with nitrates (NO_3-, groundwater drinking water standard with maximum admissible concentration of 11.3 mg NO_3-N/L) from agricultural sources poses a risk to drinking water quality and has negative impacts on the environment. At the national scale, the gross N budget is accepted as an indicator of N losses caused by NO_3-. However, there is no common EU-wide methodology for calculating N budget at the farm level for the detection of ground-and surface water pollution caused by nitrates and the monitoring of mitigation measures (Klages *et al.*, 2020). It is accepted that as the N surplus increases the risk of impact on water quality increases but the degree of the impact across different agri-climatic and soil-scapes will not be homogeneous (Fenton *et al.*, 2019). In a comprehensive study across north-western EU states by van Grinsven *et al.* (2012), the most significant environmental effect of the implementation of the Nitrates Directive since 1995 was a major contribution to the decrease of the soil N balance (N surplus), particularly in Belgium, Denmark, Ireland, the Netherlands and the United Kingdom. This decrease was accompanied by a modest decrease of nitrate concentrations since 2000 in fresh surface waters in most countries. However, this decrease was less prominent for groundwater in view of variable drainage amounts and delayed responses of NO_3^- in deep aquifers (Fenton *et al.,* 2011). As noted by Melland *et al.* (2019), positive effects on water quality in meso-catchments occurred from 1 - 10 years after decreased N surpluses were achieved, with the response time broadly increasing with catchment size. However, it took from 4 - 20 years to confidently detect the effects in water body monitoring systems. More recent studies in this area in Denmark and France have shown at measures implemented in the 1980s, resulted in a decrease in surplus N but changes to groundwater and surface water bodies only occurred years to decades later. That study concluded that 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).

The Irish agricultural landscape is heterogeneous in terms of its physical setting and even within smaller, meso-scale catchments there can be a large variability in the factors controlling N transfer and transformation. Table 4.8 shows Irish and Northern Ireland specific studies from both farm and catchment scale sorted by drainage class with corresponding N surplus and mean NO_3-N concentration in the associated water source. Leaching of N is not a steady state process and many factors control NO_3-transport and transformation in the unsaturated zone (Fenton *et al.,* 2009; Jahangir *et al.,* 2012). Such factors include both static (e.g. soil and bedrock type) and dynamic factors (e.g. agricultural management, climate, soil and bedrock thickness, soil moisture deficit, depth to water table) which are spatially and temporally variable across any dairy farming landscape (Huebsch *et al.,* 2015; Mellander *et al.,* 2018; Fenton *et al.,* 2019). The N removal capacity was found to vary highly between and within two ca. 10 km^2 catchments (McAleer *et al.,* 2017). At the catchment scale there was a poor link with the surplus NO_3-N leached to the groundwater and the concentrations of NO_3-N monitored in the catchment river outlet. For example, in one catchment the NO_3-N concentration in the shallow groundwater locally reached 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 possibly also mixing of deeper groundwater (Mellander *et al.,* 2014). 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). Therefore, a reduction in N surplus can enable N load transfer to groundwater to decrease over time leading to improvements in water quality in some areas after hydrologic and biogeochemical time lags (including immobilisation, attenuation capacity) are considered (e.g. NO_3^- improvements in free draining soils and ammonium (NH_4^+) improvements in poorly drained soils). In heavier textured soils emissions along other pathways (e.g. gaseous emissions) must also be considered and conversion of NO_3^- to NH_4^+ which can be lost to surface water along intercepting artificial drainage systems.

It is apparent that a reduction in N inputs (in both feed and fertiliser) on dairy farms clearly reduces the farm N surplus and increases NUE. When N fertiliser reduction results in insufficient on-farm grown feed, then feed external to the farm must be purchased which increases costs and externalises the impact of the farming system. A recent study investigating NUE across several EU countries highlighted the importance of accounting for externalised feed supply and manure management when comparing different farming systems (Quemada *et al.*, 2020). The relationship between N surplus and water quality is complex due primarily to the effect of soil and aquifer type. Soils and aquifers vary in their ability to reduce NO_3-N during transport which results in concentrations that both meet and fail to meet environmental standards independent of N surplus.

Table 4.8 Irish and Northern Ireland specific studies from farm scale and catchment scale studies sorted by drainage class with corresponding N surplus (kg N/ha) and mean NO_3-N concentration in the associated water source

Soil drainage	Water source	N surplus kg N/ha	Mean NO_3-N concentration mg/L	Reference
Good	Groundwater	263	16.5	Fenton *et al.* (2017)
Good	Groundwater	198	11.6	Huebsch *et al.* (2013)
Good	Soil solution	126	23.9	McCarthy *et al.* (2015)
Moderate-well	Groundwater	243	4.1	Jahangir *et al.* (2012) Clagnan *et al.* (2019)
Moderate-well	Soil solution	272	8.2	Richards *et al.* (2015)
Moderate-well	Soil solution	124	5.9	Richards *et al.* (2015)
Moderate	Drainage	92	3.0	Watson *et al.* (2000; 2007)
Moderate	Drainage	186	5.1	Watson *et al.* (2000; 2007)
Moderate	Drainage	281	8.5	Watson *et al.* (2000; 2007)
Moderate	Drainage	378	13.7	Watson *et al.* (2000; 2007)
Moderate	Drainage	481	15.3	Watson *et al.* (2000; 2007)
Moderate-poor	Groundwater	138	1.7	Humphreys *et al.* (2008)
Moderate-poor	Groundwater	153	1.3	Humphreys *et al.* (2008)
Moderate-poor	Groundwater	208	1.3	Humphreys *et al.* (2008)
Moderate-poor	Groundwater	307	3.0	Humphreys *et al.* (2008)
Moderate-poor	Groundwater	166	2.7	Burchill *et al.* (2014)
Poor	Groundwater	137	0.6	Jahangir *et al.* (2012)
		Agricultural Catchments		
Well, Timoleague	Groundwater	225*	4.9 8.5*** 6.2	McAleer *et al.* (2017) Dupas *et al.* (2017) Mellander *et al.* (2014)
Well, Castledockerell ****	Groundwater	65**	8.1 6.9	McAleer *et al.* (2017) Mellander *et al.* (2014)
Well Cregduff	Groundwater	180*	1.4	Unpublished
Moderate Dunleer	Groundwater	220*	0.9	Unpublished (2009-2020)
Poor Ballycanew	surface water	200*	2.6	Unpublished (2009-2020)
Poor Corduff	Surface water	180*	1.4	Unpublished (2010-2020)

*assumed 25% NUE, ** assumed 50% NUE, ***Shallow groundwater, ****Ca. 30% in grassland (dominated by arable land)

5. Economic analysis: effect of fertiliser N application rate on dairy farm profitability

5.1 Modelling approach

To evaluate the economic effect of chemical N application rate on farm profitability MDSM model (Shalloo *et al.*, 2004) and the PBHDM model (Ruelle *et al.*, 2015) was used. The MDSM used the biological data from the MoSt Grass Growth Model (Ruelle *et al.*, 2018) in terms of pasture growth and utilization efficiency to simulate a number of dairy farm scenarios. The MDSM model integrates animal inventory and valuation, milk production, feed requirement, land, labour, variable and fixed costs. Variable costs (including fertiliser, contractor charges, medical and veterinarian, artificial insemination, silage and reseeding) and fixed costs (machinery maintenance and running costs, farm maintenance, car, telephone, electricity, depreciation, insurance, etc), and revenue (milk, calf, and cull cow) were based on current prices (Teagasc, 2018). The economic analysis was based on a 40-ha dairy using physical and financial performance data as outlined in Teagasc Dairy Roadmap 2027 target system. The feeds offered (pasture, silage, and purchased feed) were determined by the MDSM, meeting the cow's energy requirements for maintenance, milk production, and body weight change.

Purchased feed was assumed to cost €250 per ton. Base milk price was 29.0 cents per litre plus VAT of 5.4% for milk assuming reference milk content of 36.0 g/kg fat and 33.0 g/kg protein, and a relative milk price ratio for fat to protein of 1:1.5. It was assumed that all calves were fed 4 L of whole milk per day and were sold from the farm at four weeks of age. Male calves were assumed sold for market value of €105. Heifer calves were assumed sold for market value of €350. Replacement females were purchased one month prior to calving at an estimated cost of €1,545 each (Shalloo *et al.*, 2014). Cull cow values were based on body weight at the end of lactation, an assumed kill-out rate (45%), based on the findings of Minchin *et al.* (2009), and carcass value of €2 per kg. Cull cows were assumed to have left the farm as they stopped milking with a small number of animals leaving during the year and the bulk of animals leaving at the end of lactation. It was assumed that there was no feeding period included for these animals. Labour costs were estimated at €15.00 per h and labour use at 16 h/cow per yr. Labour requirement was divided between time associated with the cow and other farm tasks (milking, grassland management, and maintenance, calf care, cleaning, veterinary and miscellaneous). The milk production and reproductive performance/calving pattern and all other parameters were taken from the Teagasc Roadmap 2020 which sets out performance and financial targets for dairy farmers formulated based on consultation with many experts.

Three N application rates were evaluated: 250, 225 and 200 (kg N/ha). The influence of N fertiliser application rate on grass growth was obtained from MoSt Grass Growth Model (Ruelle *et al.*, 2018). The effect of soil texture and agroclimatic location was small therefore the average grass production for the four scenarios (sandy loam, clay loam, Moorepark meteorological conditions and Ballyhaise meteorological conditions) was used. The corresponding grass production was 13,378, 13,773 and 14,167 kg DM/ha for N application rates 200, 225 and 250 kg N/ha, respectively.

As N application rate reduced, so did grass production and this resulted in reduced cow numbers. Animal performance was not influenced by the reduced grass growth rates.

The MSDM evaluated the impact of reduced N application rate on dairy farm profitability using three different farm scenarios:

Scenario 1: Cow numbers, variable and fixed costs reduce in line with reduced grass production.

Scenario 2: Similar to scenario 1 with the exception that fixed costs are not reduced in line with reduced cow numbers.

Scenario 3: Cow numbers are fixed - using purchased feed to fill the feed deficit. The feed deficit was fulfilled by the purchase of a mixture of grass silage and concentrate with a ratio of 2:1. No performance change was simulated in this analysis as it was assumed that individual animal energy intake would not change with this diet. There was an increase in labour assumed to feed the purchased feed.

5.2 Results

Table 5.1 shows the impact of chemical N application rate on dairy cow numbers, fixed and variable costs and farm profitability. As N fertiliser levels reduced, cow numbers, total receipts and total costs reduced. However, the reduction in receipts was higher than the reduction in costs which resulted in the profitability decreasing as chemical N fertiliser application rate reduced. A reduction in fertiliser N of 10% and 20% corresponded to a reduction in net profit of €3,647 and €6,400, respectively, at the farm level and a reduction of €87 and €160 per hectare, respectively.

Table 5.1 Cow numbers, variable and fixed costs reduce in line with reduced grass production (Scenario 1)

N chemical application rate (kg N/ha)		**250**	**225**	**200**
Physical	Cows	110	107	105
	Stocking rate (cows/ha)	2.63	2.56	2.48
	Milk produced (kg)	601,520	585,113	570,218
	MS sales (kg)	50,010	48,646	47,408
Receipts	Milk receipts	213,267	207,450	202,170
	Livestock receipts	23,746	23,187	22,685
	Total Receipts	**237,013**	**230,638**	**224,855**
Variable costs	Purchased feed	13,251	12,939	12,659
	Fertiliser	14,400	13,572	12,736
	Replacement costs	20,973	20,479	20,035
	Veterinary and AI	11,465	11,197	10,956
	Silage	5,409	5,559	5,626
Fixed costs	Labour	24,617	24,037	23,517
	Depreciation	14,752	14,566	14,399
	Interest	8,029	7,962	7,903
	Electricity	3,230	3,163	3,103
	Insurance	9,040	8,945	8,859
	Total Costs	**143,989**	**141,079**	**138,228**
Net margin	Per farm	93,071	89,604	86,671
	Per hectare farmed	2,327	2,240	2,167

Table 5.2 shows the impact of reduced chemical N fertilization where cow numbers are reduced, variable costs is reduced in line with cow numbers but fixed costs are held constant on farm. In this scenario net margin per hectare reduced by €110/ha and €204/ha when chemical N fertiliser levels were reduced from 250 kg N/ha to 225 and 200 kg/ha respectively

Table 5.2 Cow number and variable costs reduce in line with reduced grass production, while fixed costs were held constant (Scenario 2)

N chemical application rate (kg N/ha)		250	225	200
Physical	Cows	110	107	105
	Stocking rate (cows/ha)	2.63	2.56	2.48
	Milk produced (kg)	601,520	585,113	570,218
	MS sales (kg)	50,010	48,646	47,408
Receipts	Milk receipts	213,267	207,450	202,170
	Livestock receipts		23,187	22,685
	Total Receipts	**237,013**	**230,638**	**224,855**
Variable costs	Purchased feed	13,251	12,939	12,659
	Fertiliser	14,400	13,572	12,736
	Replacement costs	20,973	20,479	20,035
	Veterinary and AI	11,465	11,197	10,956
	Silage	5,409	5,559	5,626
Fixed costs	Labour	24,617	24,617	24,617
	Depreciation	14,752	14,752	14,752
	Interest	8,029	8,029	8,029
	Electricity	3,230	3,163	3,103
	Insurance	9,040	9,040	9,040
	Total Costs	**143,989**	**142,007**	**139,991**
Net margin	Per farm	93,071	88,676	84,909
	Per hectare farmed	2,327	2,217	2,123

Table 5.3 shows the impact 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 and €8,322 for reductions in chemical N fertiliser of 25 and 50 kg/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). Overall farm profitability is reduced by €4,622 and €8,951 at chemical N fertiliser rates of 225 and 200 kg/ha, respectively. Net margin per hectare is reduced by €116/ha and €224/ha, respectively.

Table 5.3 Cow numbers held constant with reduced grass production using purchased feed to fill the deficit (Scenario 3)				
N chemical application rate (kg N/ha)		**250**	**225**	**200**
Physical	Cows	110	110	110
	Milk produced (kg)	601,520	601,520	601,520
	Stocking rate (cows/ha)	2.63	2.63	2.63
	MS sales (kg)	50,010	50,010	50,010
Receipts	Milk receipts	213,267	213,267	213,267
	Livestock receipts	23,746	23,746	23,746
	Total Receipts	**237,013**	**237,013**	**237,013**
Variable costs	Purchased feed	13,251	17,490	21,573
	Fertiliser	14,400	13,615	12,843
	Replacement costs	20,973	20,973	20,973
	Veterinary and AI	11,465	11,465	11,465
	Silage	5,409	5,859	5,951
Fixed costs	Labour	24,617	25,341	26,065
	Depreciation	14,752	14,752	14,752
	Interest	8,029	8,029	8,029
	Electricity	3,230	3,230	3,230
	Insurance	9,040	9,040	9,040
	Total Costs	**143,989**	**148,617**	**152,943**
Net margin	Per farm	93,071	88,449	84,120
	Per hectare farmed	2,327	2,211	2,103

5.2.1 Financial implications Teagasc Roadmap 2027

Sensitivity analysis was completed on the impact of reduced chemical fertiliser N under the Teagasc Roadmap 2027 scenario, i.e. the average Irish dairy farm https://www.teagasc.ie/publications/2020/road-map-2030-dairy.php. This scenario is based on 170 kg/ha of chemical fertiliser N. The implications of reducing chemical fertiliser N by 10% and 20% were simulated similarly to the analysis completed in the Teagasc Target system. Scenarios simulated included chemical fertiliser N levels of 170 kg/ha, 153 kg/ha and 136 kg/ha with reducing cow numbers. The corresponding profitability/ha for N application rates of 170 kg/ha, 153 kg/ha and 136 kg/ha were €1,125/ha, €1,055/ha, and €1,010/ha, respectively. A 20% reduction in chemical N application rate per hectare (170 vs. 136 kg N/ha) reduced farm profitability by 10.2% where cow number were reduced. In a scenario where cow numbers were maintained by purchasing feed onto the farm rather than reducing cow numbers, the reduction in farm profitability was greater.

5.2.2 Implications for greenhouse gas emissions

The impact of reducing chemical fertiliser N on GHG emissions was modelled using the Teagasc Moorepark Dairy Systems Model (Shalloo *et al.*, 2004) and the Teagasc Moorepark GHG emissions model (O'Brien *et al.*, 2015). The analysis was completed using a Life Cycle Assessment framework to ensure the effect on all emissions was fully captured within the analysis. Reducing chemical fertiliser N application from 250 to 225 and 200 kg per hectare resulted in a reduction of GHG emissions of 315 and 623 kg CO_2 eqv per hectare, respectively. Reduced cow numbers were associated with a reduction of 153 and 305 kg CO_2 eqv per hectare. Other emission reductions (associated with reduced cow numbers) accounted for a reduction of 98 and 193 kg CO_2 eqv for a reduction of 25 kg/ha and 50 kg/ha, respectively. Total emissions were reduced by 566 and 1,121 kg CO_2 eqv per hectare for a reduction of 25 and 50 kg N/ha, respectively. When the GHG emissions information was linked to the financial information under the reducing cow scenario, the marginal abatement costs for GHG emissions were approximately €150 per tonne of CO_2 eqv for reducing chemical N. In the scenario where cow numbers were reduced and fixed costs were held constant, the marginal abatement costs were approximately €187 per tonne of CO_2 eqv for reducing chemical fertiliser N.

In a fixed cow scenario reducing chemical fertiliser N from 250 kg/ha to 225 kg/ha and 200 kg/ha resulted in a reduction in emissions by 335 and 636 kg CO_2 eqv, respectively. Changes in the diet due to a shorter grazing season was associated with an increase in methane emissions of 111 and 157 kg CO_2 eqv per hectare as fertiliser N levels were reduced by 25 and 50 kg N/ha, respectively. Increased purchased feed was associated with increased emissions of 221 and 402 kg CO_2 eqv per hectare, respectively, in order to supply the deficit in feed. Other emission categories were relatively static as cow numbers and animal performance did not change. Total emissions changed little when chemical fertiliser N was reduced by imported feed onto the farm. When linked with the economic information it is clear that the marginal abatement costs are large when farmers reduce chemical fertiliser N and replace the feed foregone with purchased feed while keeping cow numbers constant.

5.2.3 Implementations for ammonia emissions

Reducing chemical N application rate from 250 kg/ha to 225 kg and 200 kg/ha reduced ammonia emissions to 94.9 and 91.5 kg/ha, respectively. In the scenario where cow numbers were fixed and purchased feed was brought onto the system to replace the feed foregone, the ammonia levels per hectare did not change with reduced chemical fertiliser N.

All options to reduce chemical fertiliser N reduce the profitability of the dairy business. How farmers will react to these challenges is unknown. However, it is a strong possibility that many farmers will decide to hold cow numbers, increase purchased feed with a consequent reduction in the profitability of their business. Care should be taken to avoid a scenario where farmers move away from the grass-based system as it could result in an increase in the importation of supplementary feeds onto dairy farms. This could lead to externalisation of feed production impacts, increase land required for production, increased environmental losses for some environmental metrics, in particular land-use change and increase soil carbon loss, loss of the grass-based image and a reduction in farm profitability (with or without the land use change implications depending on the source of the feed).

6. Economic analysis: effect of chemical N application rate on beef farm profitability

A similar approach as outlined above was taken for suckler calf to beef systems. The analysis was carried out using the Grange Beef Systems Model (Crosson *et al.*, 2006). Validation of grass and silage DM yields was carried out to ensure consistency with the dairy systems analysis. The economic analysis was based on a 70 ha beef farm using physical and financial performance data as outlined in Teagasc Suckler Beef Roadmap research blueprint system. Base beef price (R3 steer) was €3.75/kg carcass.

Three chemical N application rates were evaluated: 223, 200 and 178 kg N/ha. As N application rate reduced, grass growth declined and therefore, the number of cows per hectare reduced. Two scenarios were simulated; 1) land area remained constant and thus, cow numbers declined, and 2) cow numbers remained constant and thus, land area increased. Results indicated that the impact of both scenarios was similar in respect of biotechnical performance, farm economics and GHG emissions and therefore, only Scenario 1 (fixed land area) is reported. A scenario representing the purchase of supplementary feeds to replace the loss in forage productivity was not included given the economics of suckler beef systems.

Table 6.1 shows the impact of chemical N application rate on whole farm performance. As chemical fertiliser N rates reduced, cow numbers, organic N output and stocking rate reduced. Compared to the Base scenario, reducing chemical fertiliser N rate by 20% reduced gross margin by 7% and net margin by 12%. Greenhouse gas emissions reduced by 9.4% on a per ha basis and by 3.6% on a carcass weight basis.

Table 6.1 Impact of reduction in chemical N application rate on the performance of suckler calf to beef production systems

Scenario	Base	10% Reduction	20% Reduction
Total farm chemical fertiliser N (kg/ha)	223	200	178
Suckler cow numbers	98.5	95.1	91.5
Organic N output (kg/ha)	200	193	186
Stocking rate (LU/ha)	2.61	2.52	2.43
Gross output (€/ha)	2,054	1,983	1,909
Gross margin (€/ha)	1,030	995	957
Net margin (€/ha)	430	405	377
Net margin (Farm €)	30,100	28,350	26,390
GHG emissions (t CO_2e/ha)	9.6	9.1	8.7
GHG emissions (kg CO_2e/kg carcass)	22.0	21.5	21.2

7. Economic analysis: effect of chemical N application rate on sheep farm profitability

The economic effect of chemical N application rate on mid-season lamb production was investigated using the Teagasc Lamb Production Model (TLPM) (Bohan *et al.*, 2018). Biological data in terms of pasture growth, pasture utilization, ewe and lamb performance were obtained from Earle *et al.* (2017). The economic analysis was based on a 20-ha sheep farm using the Teagasc 2025 Sheep Roadmap comparing 145 and 113 kg N/ha (22% reduction in chemical fertiliser N rate) (Table 7.1). When N application rate was reduced from 145 to 113 kg N/ha, grass production and utilisation was reduced by 11%. On a fixed land area the reduction in grass utilisation resulted in a reduction in ewe carrying capacity by 17% and lamb output by 15%. This resulted in a reduction of net margin per hectare of 16%.

Table 7.1 Influence of chemical N application rate on grass production, animal performance and farm profitability

Chemical N application rate (kg/ha)	145	113
Grass grown (t DM/ha)	13	11.6
Grass utilised (t DM/ha)	11.1	9.3
Average ewe numbers	259	215
Ewes/ha	12	10
Stocking rate (LU/ha)	2.4	2.0
Lamb carcass output (kg/ha)	403	341
Gross output (€/ha)	2,116	1,767
Variable costs (€/ha)	1,008	825
Gross margin (€/ha)	1,107	942
Total costs (€/ha)	1,316	1,091
Net margin (€/ha)	744	628
Net margin (€/ kg lamb carcass)	1.85	1.84

8. New strategies to increase N use efficiency and reduce chemical N application rates on grassland

Nitrogen is the most limiting nutrient for productive agriculture. The principal N inputs on dairy farms are fertiliser, biologically fixed N, purchased concentrate feed, mineralised soil N and atmospheric N deposition. The relative contribution of each of these N inputs to feed production, milk production, and environmental N loss depends on several factors including milk production system. At farm level there are three indicators of N efficiency. The first is N surplus derived by subtracting the total quantities of N exported from the total quantities imported on a per hectare basis. Nitrogen use efficiency is the second indicator which is derived by dividing the total quantities (kg) of N exported by the total quantities imported, expressed as a percentage. The third is N surplus per kg of milk solids produced; this is analogous to emissions per unit of production. However, none of these indicators take into account of soil type, climatic conditions or production system.

8.1 Increasing N use efficiency

8.1.1 Low emissions slurry spreading (LESS)

Slurry is an important source of nutrients (N, P & K) and application to grassland must be properly timed to maximise the efficiency of nutrient capture and utilization, as well as replenishing soil fertility levels. The targeted application of slurry in spring, based on soil test results, will ensure the most efficient use of slurry nutrients for grass production and minimise potential NH_3 losses. Slurry N losses in the form of NH_3 emissions are potentially the largest loss of reactive N on Irish farms, with manure spreading responsible for a quarter of all NH_3 losses in Ireland. Using LESS methods, such as trailing shoe or band spreaders, has a large effect on N losses and increases slurry N value by 10%, thereby increasing pasture productivity and reducing chemical N requirements. Adequate slurry storage at farm level is required to capitalize on this.

It is estimated that spreading 90% of slurry using LESS in 2030 would result in a saving of 9,622 tonnes of N/year in 2030; additionally it would reduce NH_3 loss by 11.69 kilotonnes and a reduce GHG emissions by 0.21 Mt of CO_2 eqv per year.

8.1.2 Precision grazing management

Nitrogen use efficiency on grassland farms can be increased through greater use of grass measurement. As outlined in Section 2.2 of this report increase grass utilisation accounted for 69% of the increase in productivity between 2010 and 2019. The number of grassland farmers using PastureBase Ireland has increased significantly in recent years. Knowledge of farm grass cover (grass availability on farm) and current grass growth rates can lead to more efficient use of chemical fertiliser N. Additionally increased grass production combined with higher grass utilisation will result in increased NUE. The average grass production on dairy farms, using PastureBase Ireland data, over the past 7 years (2013 to 2019) is 13 t DM/ha and those farms have an average of 263 grazing days. National Farm Survey data indicates that the national average grass production on dairy farms is just over 10 t DM/ha and utilisation just over 8 t DM/ha. Increasing DM production and utilisation on grassland farms will reduce the requirement for supplementation which is another source of N and will result in increased NUE.

8.1.3 Protected urea fertiliser

Recent studies have shown that protecting urea with a urease inhibitor reduces loss of NH_3 to the environment by 80%. Furthermore, protected urea reduces N_2O losses by 71% compared with ammonium nitrate, without compromising productivity. Teagasc research has shown that protected urea grows the same amount of grass as CAN under actual cow grazing conditions (McCarthy per comm). Currently protected urea is at a lower cost per unit of N than CAN. Protected urea can help reduce N losses to water by holding N in the ammonium form, which is more stable in soil particularly during wet conditions.

It is estimated that a shift to using 191,500 tonnes of protected urea by 2030 would result in a saving of 3,100 tonnes of N per annum and a reduction of 0.582 Mt of CO_2 eqv per year.

8.1.4 Reducing concentrate crude protein content

On average, Irish dairy cows have a requirement for a diet with a crude protein (CP) content of 15 to 17%. In general, high quality grazed pasture has a CP content of approximately 18% during the grazing season. Therefore, grazed grass more than adequately meets animal requirements for CP. Several studies have been completed during the last 10 years that showed no benefit from feeding rations with high CP content at pasture. Indeed, feeding high CP content concentrates during the grazing season provides excess CP to the dairy cow, who must then expend energy to excrete the excess N. From an environmental perspective, reducing concentrate CP content will reduce N surplus and loss to the environment. A 1% reduction in CP of dairy concentrates reduces N excretion by 1.6 kg. On that basis, using concentrates with a CP content of 12 to 14% is recommended when animals are at pasture.

8.1.5 Increasing soil fertility

Increasing soil fertility (pH, P and K) has been shown to increase NUE (Wall, 2019), only where it is sub optimum. In a long term soil fertility study, NUE for grass production increased from 57% in a low pH soil to 68% on a high pH soil on two contrasting soil types (Fox *et al.*, 2015). Additionally it showed that where soil pH, P and K were optimised, greater than 70% NUE was achieved. Additionally, a recent study across 21 intensive dairy farms in Ireland showed that NUE was 50% in P index I soils while it was 59% in P index 3 soils (Murphy *et al.*, 2020). Therefore, more frequent soil fertility testing and greater use of nutrient management planning will increase NUE on grassland farms.

It is estimated that an increase of 43,000 ha/year at optimal soil pH between 2020 and 2030 would result in a saving of 15,372 tonnes of N/year and a reduction of 0.112 Mt of CO_2 eqv per year.

8.1.6 Role of micronutrients

On Irish soils the key micronutrients essential for plant growth that may require supplementation and management are typically zinc (Zn), copper (Cu), manganese (Mn), molybdenum (Mo) and boron (B). Micronutrient deficiencies are more likely to be more prevalent in soil with very high pH (>7.0), sandy textured soils and soils with very low soil organic matter concentrations. In a survey of grassland farms (n=102) across Ireland (Kavanagh *et al.*, 2014), the mineral concentrations in grass offered to grazing animals was not consistent all year round. The concentrations of N, P, K, S, Na, Cu, Zn and Mo tended to be lower in summer (May and/or July) compared with Spring (February) or Autumn (October), whereas, the concentrations of Ca, Mg and Mn levels in grassland were more consistent throughout the year and less affected by seasonality of grass growth. This study concluded that herbage nutrient concentrations were generally sufficient for sustaining growth; however, further supplementation with certain nutrients, particularly K and Mg on land used for silage conservation, may be required during periods of peak growth in late spring and early summer on some farms. While there may be limited pasture growth response to micronutrient applications under Irish conditions, the importance of micronutrient levels relates principally to satisfying animal needs (Wall and Plunkett (eds.), 2016). A recent study of pasture taken across 44 Irish dairy farms concluded that, on average, pasture grown on Irish dairy farms is inadequate for P, Cu, I, Zn, and Se to meet cow requirements when fed as the sole feed (Curran *et al.,* 2016). Nutrient interactions should also be considered as they can exhibit controlling processes that influence the uptake and availability of other nutrients. For example, high Mo in herbage reduces the adsorption of Cu by ruminant animals whereas, high N and S application rates have been shown to reduce selenium (Se) levels in grass herbage below toxic levels (Fleming 1970; Wall and Plunkett (eds.), 2016). Overall a balanced approach to maintaining soil fertility and protecting soil quality will be required to enhance soil biology and maximise the production potential of grassland soils while achieving high levels of nutrient use efficiency and environmental sustainability.

8.2 Reducing chemical N application

8.2.1 Grass clover swards

Traditionally, white clover (*Trifolium repens* L.) was included in perennial ryegrass mixtures to improve sward nutritive value and reduce N fertiliser use. The availability of cheap N fertiliser, however, reduced the variability in pasture production during spring and increased overall pasture production. This led to a reduction in the use of white clover, with declining levels reported in temperate grazing regions such as Western Europe and New Zealand. Managing grassland with less mineral N fertiliser inputs and with greater reliance on biological N fixation from white clover can reduce costs (less chemical fertiliser N), reduce GHG emissions (industrial synthesis of mineral N fertiliser is energy intensive) and increase the digestibility of herbage. Dineen *et al.* (2018) undertook a meta-analysis by compiling data from multiple studies to quantify the milk production response associated with the introduction of white clover into perennial ryegrass swards. They found that, at a mean sward white clover content of 32%, mean daily milk and milk solids yield per cow were increased by 1.4 and 0.12 kg/day, respectively, compared with grass only swards. The same studies indicated that, although stocking rate (-0.25 cows/ha) and N fertiliser application rate (-81 kg/ha) were reduced on perennial ryegrass-white clover swards, milk and milk solids output per ha was unaffected. The results of the meta-analysis indicate that there is potential to replace up to 100 kg fertiliser N/ha, while maintaining output and profitability on intensive dairy farms where white clover content is 20% to 25% of the annual sward biomass.

Results from recent research investigating the incorporation of white clover into perennial ryegrass swards in Teagasc Moorepark and Teagasc Clonakilty Agricultural College has also shown the potential of perennial ryegrass-white clover swards to increase the productivity and profitability of Irish grazing systems. Pasture production increased by 8% in Clonakilty when white clover was included in the sward (at a similar N fertiliser rate of 250 kg N/ha; McClearn *et al.*, 2019) whereas in Moorepark, although pasture production did not increase significantly, the perennial ryegrass-white clover swards receiving 150 kg N/ha grew the same quantity of pasture as the perennial ryegrass-only swards receiving 250 kg N/ha (Egan *et al.*, 2018). Perennial ryegrass-white clover swards tend to be higher quality in mid-season compared to perennial ryegrass-only swards as sward white clover content increases from May onwards. Moorepark and Clonakilty research both show increases in milk and milk solids (MS; kg fat + protein) production from perennial ryegrass-white clover swards compared to perennial ryegrass-only swards (Table 8.1; Egan *et al.*, 2018; McClearn *et al.*, 2019).

Table 8.1 Effect of white clover inclusion on pasture production, milk and milk solids yield in Teagasc Moorepark (2013-2016) and Teagasc Clonakilty (2014-2017) grazing experiments

Teagasc Moorepark experiment	**Grass-only 250 kg N/ha**	**Grass-clover 250 kg N/ha**	**Grass-clover 150 kg N/ha**
Pasture production (t DM/ha)	13.7	14.0	13.7
White clover content (%)	-	23	27
Milk yield (kg/cow)	6,108	6,498	6,466
Milk solid yield (kg/cow)	460	496	493
Teagasc Clonakilty experiment	**Grass-only 250 kg N/ha**		**Grass-clover 250 kg N/ha**
Pasture production (t DM/ha)	15.6		16.8
White clover content (%)	-		23
Milk yield (kg/cow)	5,222		5,818
Milk solid yield (kg/cow)	437		485

McClearn *et al.* (2020) reported an economic analysis of the biological results from the Clonakilty experiment and showed that including white clover into perennial ryegrass swards increased profitability by €305/ha. On-going analysis of the trial results indicate that the combined animal performance gains and cost savings from reduced N fertiliser use in perennial ryegrass-white clover swards has the potential to significantly increase annual farm profitability, while also reducing GHG emissions by up to 10%.

There are, however, challenges with the adoption of white clover on dairy farms. The use of white clover is not widespread on grassland farms, and may be problematic on heavy soils. Establishing white clover, in sufficient quantities, i.e. an annual sward white clover content of 20% to 25%, on dairy farms in order to reduce N fertiliser use remains a challenge. Improved methods of sowing and management at and after sowing are required for establishment. Excellent grazing management is required at farm level in order to maintain a high level of clover in grassland pastures. The yield stability of white clover in intensively managed pastures remains problematic, the limited range of white clover safe grassland herbicides and the risk of bloat in grazing livestock have discouraged some farmers. While research has shown the possibilities for overcoming these obstacles through improved grazing management, over-sowing swards and the use of bloat prevention technologies, further work is required to increase the stability and persistency of white clover and more generally encourage greater adoption.

It is estimated that incorporating white clover into 23,286 ha of grassland pastures per year between 2021 and 2030 would result in a saving of 19,140 tonnes of N fertiliser/year in 2030; additionally would reduce NH_3 loss by 0.64 kilotonnes and reduce GHG emissions by 0.041 Mt of CO_2 eqv per year.

9. Conclusions

Over the period 2010 to 2019, the expansion in the dairy industry in recent years has resulted in an increase in land area allocated to dairy farming; at farm gate level the expansion has resulted in an increase in N surplus, increases in N use efficiency and lower emissions of N per unit of production. Stocking rates increased by 13% (1.80 to 2.03 cows/ha) and level of chemical N fertiliser per hectare has increased by 15% (161 to 185 kg/ha). Over the nine year period, grass utilisation increased from 6.7 to 8.0 t DM/ha. Over the period 31% of the increase in grass utilisation originated from increased chemical N with the remainder coming from increased grassland efficiency. The most recent EPA report on Water Quality in Ireland (2013-2018), found that 52.8% of surface water bodies assessed are in satisfactory ecological health being either good or high ecological status. The remaining 47.2% of surface water bodies are in moderate, poor or bad ecological status. This compares to 55.4% at satisfactory status for the last assessment period of 2010-2015, a decrease of 2.6%.

Modelling the economic impact of reducing chemical N application rate by 25 and 50 kg N/ha when using 250 kg N/ha reduced farm profitability by €4,622 (5%) and €8,951 (10%), respectively. The GHG marginal abatement costs were large when the reduced grass DM production is replaced with imported feed onto the farm. Technologies in relation to incorporating white clover into existing pastures, increased soil fertility (including soil pH), use of low emission slurry spreading and greater use of precision grazing management have the potential to elevate these negative economic impacts of reduced chemical N at farm level. This will require a significant knowledge transfer programme over a number of years to get these technologies adopted at farm level.

Grass-based systems into the future need to focus on maximising grass production and utilisation, increase nutrient use efficiency and minimising the amount of feed imported onto the farm. This is both more profitable and environmentally more sustainable. A move to lower grass production carries the risk of greater importation of feed onto the farm which will lead to reduced profitability and a deterioration in environmental sustainability as has been demonstrated around the world.

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11. Appendices

Appendix 11.1. Mean (sd) temperature, monthly rainfall and solar radiation over 16-years for Ballyhaise and Moorepark

	Agriclimatic region	*Jan*	*Feb*	*March*	*April*	*May*	*June*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*
Mean T	Ballyhaise	**4.7 (1.7)**	**4.7** (1.1)	**5.9** (1.4)	**8.2** (1.2)	**10.7** (0.8)	**13.8** (0.9)	**15.0 (1.2)**	**14.5 (0.7)**	**12.7 (0.8)**	**10.1** (1.1)	**6.6 (1.3)**	**5.0 (2.0)**
	Moorepark	5.6 (1.3)	5.4 (1.1)	6.6 (1.2)	8.8 (1.0)	11.4 (0.7)	14.3 (0.9)	15.6 (1.1)	15.0 (0.8)	13.3 (0.8)	10.6 (1.0)	7.5 (1.3)	6.1 (1.8)
Rainfall	Ballyhaise	100 (43)	75 (36)	73 (26)	60 (24)	71 (30)	64 (38)	86 (32)	95 (34)	80 (43)	92 (36)	98 (45)	111 (57)
	Moorepark	107 (39)	78 (56)	79 (28)	67 (39)	71 (23)	76 (47)	80 (35)	73 (51)	74 (33)	97 (43)	107 (58)	105 (66)
Solar radiation	Ballyhaise	**202 (24)**	**422** (39)	**778** (97)	**1281** (139)	**1588** (126)	**1644 (187)**	**1531 (165)**	**1236 (113)**	**916** (59)	**529** (60)	**275 (33)**	**159** (20)
	Moorepark	250 (30)	459 (55)	821 (97)	1292 (137)	1555 (129)	1715 (218)	1515 (188)	1315 (110)	956 (86)	550 (59)	314 (34)	189 (23)

Appendix 11.2. Impact of soil texture, agroclimatic region and chemical N application rate on seasonal grass growth (sd) and nitrogen response

Soil type	*Agroclimatic region*		*Spring*		*Summer*		*Autumn*		*Winter*		*Annual*		*N response*
Sandy loam	Moorepark	0	1,479	(395)	4,442	(401)	2,588	(241)	358	(80)	8,868	(824)	
		50	1,720	(422)	5,019	(384)	2,855	(240)	395	(86)	9,988	(842)	22.4
		100	1,933	(449)	5,508	(392)	3,156	(240)	429	(92)	11,026	(862)	20.7
		150	2,121	(469)	5,956	(403)	3,437	(247)	459	(96)	11,973	(856)	18.9
		200	2,300	(499)	6,385	(428)	3,683	(261)	492	(101)	12,859	(879)	17.7
		250	2,465	(529)	6,780	(435)	3,894	(266)	520	(104)	13,660	(899)	16.0
		300	2,609	(544)	7,158	(452)	4,091	(269)	549	(108)	14,406	(921)	14.9
	Ballyhaise	0	1,683	(476)	4,407	(514)	2,370	(757)	426	(96)	8,887	(1,372)	
		50	1,936	(504)	4,962	(527)	2,621	(858)	472	(100)	9,991	(1,511)	22.1
		100	2,167	(524)	5,438	(523)	2,894	(928)	516	(105)	11,014	(1,576)	20.5
		150	2,384	(547)	5,899	(553)	3,159	(951)	561	(113)	12,003	(1,621)	19.8
		200	2,579	(570)	6,315	(589)	3,379	(993)	600	(120)	12,873	(1,697)	17.4
		250	2,761	(591)	6,702	(616)	3,575	(1,035)	636	(126)	13,674	(1,764)	16.0
		300	2,928	(607)	7,067	(641)	3,756	(1,093)	669	(131)	14,420	(1,857)	14.9
Clay loam	Moorepark	0	1,743	(461)	5,054	(497)	2,731	(375)	170	(135)	9,697	(897)	
		50	1,979	(490)	5,617	(502)	3,036	(387)	199	(139)	10,832	(869)	22.7
		100	2,219	(529)	6,130	(532)	3,299	(405)	227	(143)	11,875	(878)	20.9
		150	2,424	(576)	6,590	(563)	3,525	(419)	253	(146)	12,793	(894)	18.4
		200	2,591	(607)	7,013	(583)	3,747	(441)	275	(151)	13,626	(910)	16.7
		250	2,727	(629)	7,400	(601)	3,976	(464)	296	(155)	14,399	(937)	15.5
		300	2,846	(656)	7,747	(624)	4,193	(475)	316	(159)	15,101	(964)	14.0
	Ballyhaise	0	1,949	(605)	5,173	(518)	2,837	(400)	270	(173)	10,229	(823)	
		50	2,205	(638)	5,721	(547)	3,132	(405)	305	(180)	11,363	(823)	22.7
		100	2,427	(674)	6,225	(591)	3,395	(411)	339	(187)	12,387	(844)	20.5
		150	2,630	(712)	6,675	(621)	3,640	(421)	371	(192)	13,316	(865)	18.6
		200	2,806	(748)	7,087	(661)	3,864	(439)	397	(196)	14,154	(886)	16.8
		250	2,951	(761)	7,471	(684)	4,090	(458)	424	(200)	14,936	(919)	15.6
		300	3,081	(780)	7,815	(701)	4,303	(468)	449	(206)	15,648	(944)	14.2

Appendix 11.3 Influence of soil type, agroclimatic region and stocking rate on grass production, grazing days (sd) and feed budget (sd) using 100 kg N/ha

	Agroclimatic region	*SR (cow/ha)*	*Grass growth (ha)*	*Number day without silage supplementation*		*Grass intake (kg DM/cow)*		*Silage fed (kg DM/cow)*		*Grass intake (kg DM/ha)*		*Surplus deficit (kg DM/ha)*	
Sandy loam	Ballyhaise	2	10,517	192	(27)	3419	(161)	1,326	(172)	6,837	(322)	-382	(707)
		2.25	10,771	177	(28)	3330	(148)	1,409	(167)	7,491	(334)	-1,183	(712)
		2.5	11,002	172	(27)	3284	(153)	1,453	(165)	8,209	(383)	-1,980	(709)
		2.75	11,279	162	(28)	3220	(167)	1,508	(176)	8,856	(459)	-2,761	(783)
		3	11,558	148	(29)	3133	(154)	1,577	(167)	9,398	(462)	-3,552	(755)
	Moorepark	2	10,515	198	(51)	3432	(302)	1,313	(304)	6,863	(605)	-334	(1,080)
		2.25	10,759	178	(51)	3307	(356)	1,427	(335)	7,441	(800)	-1,156	(1,124)
		2.5	11,026	168	(45)	3260	(329)	1,467	(293)	8,149	(822)	-1,931	(1,045)
		2.75	11,270	160	(47)	3196	(342)	1,515	(306)	8,790	(941)	-2,718	(1,088)
		3	11,499	149	(44)	3099	(321)	1,583	(286)	9,296	(962)	-3,505	(1,138)
HS	Ballyhaise	2	11,536	187	(29)	2745	(370)	1,924	(356)	5,491	(740)	77	(706)
		2.25	11,709	183	(26)	2712	(338)	1,953	(324)	6,102	(760)	-793	(704)
		2.5	11,885	180	(31)	2719	(388)	1,958	(365)	6,798	(971)	-1,658	(791)
		2.75	12,057	177	(30)	2688	(374)	1,970	(353)	7,392	(1,029)	-2,478	(837)
		3	12,190	171	(28)	2631	(369)	2,004	(356)	7,893	(1,107)	-3,332	(911)
	Moorepark	2	12,035	198	(22)	2944	(311)	1,745	(294)	5,887	(623)	479	(645)
		2.25	12,217	192	(21)	2909	(330)	1,778	(306)	6,545	(742)	-366	(676)
		2.5	12,407	188	(20)	2899	(314)	1,796	(284)	7,246	(785)	-1,220	(629)
		2.75	12,570	184	(19)	2877	(322)	1,799	(301)	7,912	(886)	-2,036	(746)
		3	12,704	176	(23)	2793	(307)	1,851	(289)	8,380	(921)	-2,868	(736)

Appendix 11.4 Influence of soil type, agroclimatic region and stocking rate on grass production, grazing days (sd) and feed budget (sd) using 150 kg N/ha

	Agroclimatic region	*SR (cow/ha)*	*Grass growth (ha)*	*Number day without silage supplementation*		*Grass intake /cow*		*Silage fed /cow*		*Grass intake /ha*		*Surplus deficit (ha)*	
Sandy soil	Ballyhaise	2	11,548	207	(28)	3,507	(150)	1,241	(161)	7,015	(300)	367	(643)
		2.25	11,762	192	(26)	3,420	(155)	1,321	(164)	7,694	(348)	-458	(674)
		2.5	11,967	180	(32)	3,342	(181)	1,403	(190)	8,356	(454)	-1314	(740)
		2.75	12,191	173	(25)	3,301	(142)	1,427	(157)	9,078	(390)	-2076	(706)
		3	12,397	165	(22)	3,209	(125)	1,492	(134)	9,628	(374)	-2874	(713)
	Moorepark	2	11,560	213	(48)	3,529	(279)	1,221	(284)	7,059	(558)	417	(1,101)
		2.25	11,786	194	(52)	3,415	(318)	1,332	(321)	7,684	(716)	-433	(1,196)
		2.5	12,003	183	(45)	3,362	(298)	1,387	(292)	8,405	(745)	-1253	(1,135)
		2.75	12,234	178	(50)	3,301	(348)	1,422	(324)	9,077	(957)	-2016	(1,232)
		3	12,433	166	(48)	3,200	(339)	1,490	(302)	9,599	(1,016)	-2811	(1,221)
Clay loam	Ballyhaise	2	12,507	190	(26)	2,767	(348)	1,903	(333)	5,535	(697)	737	(762)
		2.25	12,660	185	(28)	2,738	(360)	1,931	(341)	6,161	(810)	-141	(763)
		2.5	12,788	181	(29)	2,728	(376)	1,945	(356)	6,821	(940)	-1038	(816)
		2.75	12,946	180	(29)	2,712	(391)	1,942	(364)	7,458	(1,077)	-1864	(851)
		3	13,064	176	(29)	2,658	(368)	1,971	(357)	7975	(1,103)	-2703	(867)
	Moorepark	2	13,015	203	(21)	2,978	(328)	1,713	(311)	5,956	(656)	1155	(689)
		2.25	13,178	198	(21)	2,955	(334)	1,737	(305)	6,649	(752)	299	(675)
		2.5	13,338	191	(18)	2,932	(314)	1,764	(285)	7,329	(784)	-570	(695)
		2.75	13,439	186	(21)	2,872	(312)	1,798	(289)	7,898	(859)	-1442	(740)
		3	13,607	182	(18)	2,822	(283)	1,820	(267)	8,465	(848)	-2236	(749)

Appendix 11.5 Influence of soil type, agroclimatic region and stocking rate on grass production, grazing days (sd) and feed budget (sd) using 200 kg N/ha

	Agroclimatic region	*SR (cow/ha)*	*Grass growth (ha)*	*Number day without silage supplementation*		*Grass intake /cow*		*Silage fed /cow*		*Grass intake /ha*		*Surplus deficit (ha)*	
Sandy loam	Ballyhaise	2	12,480	229	(23)	3,632	(147)	1,123	(132)	7,265	(295)	1057	(677)
		2.25	12,681	212	(25)	3,539	(151)	1,208	(152)	7,962	(340)	227	(647)
		2.5	12,868	194	(25)	3,451	(158)	1,301	(159)	8,627	(394)	-657	(750)
		2.75	13,049	187	(24)	3,369	(135)	1,361	(145)	9,264	(371)	-1,470	(724)
		3	13,218	176	(25)	3,272	(147)	1,424	(165)	9,817	(441)	-2,273	(795)
	Moorepark	2	12,491	227	(50)	3,607	(274)	1,147	(279)	7,215	(548)	1,065	(1,238)
		2.25	12,695	212	(49)	3,529	(289)	1,220	(290)	7,941	(650)	246	(1,206)
		2.5	12,861	202	(49)	3,462	(297)	1,287	(291)	8,655	(743)	-608	(1,190)
		2.75	13,062	187	(47)	3,359	(315)	1,368	(299)	9,236	(866)	-1,424	(1,226)
		3	13,254	178	(48)	3,275	(329)	1,416	(308)	9,825	(986)	-2,196	(1,283)
Clay loam	Ballyhaise	2	13,386	191	(27)	2,768	(363)	1,898	(347)	5,537	(726)	1,339	(823)
		2.25	13,511	188	(29)	2,752	(392)	1,916	(363)	6,192	(883)	447	(788)
		2.5	13,631	183	(26)	2,743	(368)	1,929	(340)	6,858	(919)	-455	(784)
		2.75	13,759	182	(29)	2,724	(379)	1,934	(357)	7,490	(1,041)	-1,311	(877)
		3	13,843	182	(28)	2,695	(361)	1,933	(343)	8,085	(-1,084)	-2,137	(851)
	Moorepark	2	13,907	202	(24)	2,969	(346)	1,723	(322)	5,937	(692)	1,756	(697)
		2.25	14,030	201	(20)	2,964	(330)	1,720	(304)	6,669	(742)	896	(693)
		2.5	14,159	194	(18)	2,952	(324)	1,745	(291)	7,380	(811)	-12	(680)
		2.75	14,295	188	(20)	2,881	(323)	1,788	(299)	7,921	(889)	-854	(754)
		3	14,379	184	(21)	2,837	(310)	1,797	(291)	8,511	(930)	-1,686	(810)

Appendix 11.6 Influence of soil type, agroclimatic region and stocking rate on grass production, grazing days (sd) and feed budget (sd) using 250 kg N/ha

	Agriclimatic region	*SR (cow/ha)*	*Grass growth (ha)*	*Number day without silage supplementation*		*Grass intake /cow*		*Silage fed /cow*		*Grass intake /ha*		*Surplus deficit (ha)*	
Sandy loam	Ballyhaise	2	13,350	234	(20)	3,651	(122)	1,097	(118)	7,302	(244)	1,660	(709)
		2.25	13,501	222	(19)	3,593	(115)	1,154	(119)	8,085	(259)	819	(688)
		2.5	13,664	206	(22)	3,510	(128)	1,244	(138)	8,774	(319)	-84	(745)
		2.75	13,814	194	(26)	3,409	(161)	1,318	(170)	9,375	(442)	-924	(789)
		3	13,969	189	(24)	3,350	(137)	1,345	(150)	10,050	(412)	-1,685	(772)
	Moorepark	2	13,355	233	(46)	3,634	(260)	1,119	(259)	7,268	(519)	1,663	(1,356)
		2.25	13,510	219	(48)	3,571	(272)	1,180	(272)	8,036	(612)	807	(1,325)
		2.5	13,669	211	(48)	3,527	(288)	1,227	(292)	8,817	(720)	-37	(1,294)
		2.75	13,836	197	(47)	3,423	(281)	1,304	(277)	9,414	(772)	-857	(1,270)
		3	14,000	189	(45)	3,343	(295)	1,347	(279)	10,030	(886)	-1,634	(1,297)
Clay loam	Ballyhaise	2	14,196	191	(27)	2,773	(361)	1,897	(346)	5,547	(722)	1,878	(751)
		2.25	14,301	189	(26)	2,778	(359)	1,896	(339)	6,250	(808)	984	(778)
		2.5	14,399	188	(26)	2,778	(368)	1,899	(345)	6,946	(920)	77	(794)
		2.75	14,496	185	(26)	2,746	(365)	1,912	(344)	7,551	(1,003)	-795	(820)
		3	14,604	182	(24)	2,691	(341)	1,938	(326)	8,074	(1,022)	-1,646	(838)
	Moorepark	2	14,722	206	(22)	2,992	(331)	1,698	(308)	5,984	(662)	2,321	(650)
		2.25	14,830	205	(22)	2,990	(334)	1,698	(312)	6,728	(751)	1,445	(693)
		2.5	14,933	198	(21)	2,964	(332)	1,731	(301)	7,410	(829)	521	(713)
		2.75	15,053	193	(20)	2,918	(318)	1,752	(297)	8,024	(874)	-319	(774)
		3	15,141	186	(16)	2,863	(295)	1,784	(275)	8,588	(886)	-1,181	(743)