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Modelling the Marginal Abatement Cost of Mitigating Nitrogen Loss from Agricultural Land

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Measuring the Marginal Abatement Cost of Reducing Nitrogen loss from Agriculture

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Abstract

With the deadline identified by the Water Framework Directive (2000/60/EC) approaching in 2015 there is increasing pressure on policymakers to introduce new regulations to achieve water quality targets. Agriculture is one of the contributors of diffuse pollution entering watercourses and will come under pressure to reduce pollutant loads. This paper produces Marginal Abatement Cost (MAC) Curves for eight policy measures that could potentially reduce nitrate leaching from agricultural land on Irish dairy farms. These include: 1) reduction of fertiliser application by 10%; 2) reduction of fertiliser application by 20%; 3) livestock unit reduction to limit organic N to 170 kg ha^{-1}; 4) reduction of livestock units by 20%; 5) change of feed mix to reduce cow dietary N intake; 6) fencing off watercourses to introduce a buffer zone; 7) improved dairy cow genetic merit by introducing higher performing dairy breeds; 8) more efficient slurry application. Results from this study indicate that there will be reductions in farm gross margins across nearly all policy measures. However, MAC and the ranking of MAC vary across individual farms and aggregate MAC does not reflect the heterogeneity of impacts across individual farms. This paper shows that any measure introduced in a "one size fits all command-control" fashion will not yield efficient economic results.

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I.1 Introduction

In Ireland as in other EU countries, nitrate enrichment of watercourses is both an environmental issue and a challenge. The EPA (Environmental Protection Agency) reports that in 2008 a total of 7 percent of groundwater monitoring sites failed to comply with the Irish Threshold Value concentration of 37.5 $mgNO_3/L$ and one percent failed to comply with the Drinking Water Maximum Allowable concentration of 50 mg NO_3/L. Additionally, the EPA classifies 21 % of river channels as being slightly polluted, 10 % as being moderately polluted and 0.5 percent as being seriously polluted (EPA, 2008). DEHLG (2009b) highlights that historic intensive agricultural practices have had an important contribution to the levels of Nitrogen (N) load in Irish rivers.

Nutrient losses from agriculture can pose problems to the wider aquatic environment. The main pressure on water quality comes from nutrient enrichment (Schulte *et al.* 2006). Nitrogen is an important nutrient for reproduction and growth of all organisms (Merrington *et al.*, 2002) and is abundant in the environment. Current levels of agricultural output could not be maintained without the widespread use of both synthetic and organic fertilizers (Merrington *et al.*, 2002). The N pathways and its transformations in the environment are very complex and the direct link between sources and affected areas can be difficult to establish. There are a number of studies that have attempted to link human activities and impaired water quality. Donohue *et al.* (2006) and O'Donoghue *et al.*, (2010) identify factors including intensive agricultural activity and human settlement, among others as exhibiting a high correlation with downstream water quality. This is in line with international research (Merrington, 2002; Novotny, 2003; Schulte *et al.* 2006).

As a result of these issues, a number of policy mechanisms have been introduced to improve water quality. At the EU level, the Water Framework Directive (WFD) requires that (a) all waters are restored to at least “good quality” and that (b) water currently classified as “pristine” quality is maintained. The Nitrates Directive (91/676/EEC) was introduced in 1991 to control nitrate losses from agriculture. In Ireland the Good Agricultural Practice regulations (S.I. No.610/2010) were introduced to implement the Nitrates Directive. These regulations restrict the period when application of fertilizers is allowed; the amount of manure and inorganic fertilizer applied per hectare; the distance to a water body for fertilizer application; ploughing activities; and impose requirements for minimum storage capacities for livestock manures. These restrictions apply on a whole farm basis and penalties can be applied if a breach is detected under cross-compliance. Codes of practice for nutrient management have also been implemented in Ireland within the Rural Environment Protection Scheme. There have also been substantial financial incentives for farmers in Ireland under a grant aided Farm Waste Management scheme to improve the storage of manure and waste water on farms resulting in expenditure of over €1.2 billion in mitigation measures since the scheme's introduction in 2001 (DAFM, 2011). Whilst the expectation is that the Nitrates regulations will “go a long way” towards meeting the WFD water quality objectives, additional efforts may be required at local level.

There is an extensive theoretical literature around mitigation strategies to reduce N losses from agriculture (Ritter 2001, Merrington 2002, Novotny 2003, Cuttle *et al.* 2006). However, identifying the pressure points and the policy alternatives does not provide sufficient information for efficient decision-making. The Water Framework Directive (2000/60/EC) promotes cost-benefit analysis of the measures protecting water resources to achieve environmental objectives in the most cost effective manner.

Agriculture is a heavily subsidised sector in the EU, which generates narrow profit margins for many farmers so careful analysis is needed to assess the impact of policy measures on farm income. This paper attempts to fill a gap in existing research literature and provide policy-makers with economic analysis to aid in the decision-making process concerning policies for the agricultural sector. The cost-effectiveness of different farm level N mitigation strategies will be investigated by constructing a Marginal Abatement Cost (MAC) Curve displaying the cost of each N unit reduction for each strategy. Cuttle *et al.* (2004), Hennessy *et al.* (2005) and Fezzi *et al.* (2007, 2008), undertook economic analyses of possible policy measures in this area. . In line with the research of Hennessy *et al.* (2005) and Fezzi *et al.* (2007), the economic impact of the possible N mitigation strategies is estimated. The strategies are then ranked according to their cost effectiveness. Micro and aggregate MAC curves are also constructed.

The modelling methodologies utilised in this paper are different from those previously used in similar studies. Cuttle *et al.* (2004) and Hennessy *et al.* (2005) used a linear programming approach for their estimations. Fezzi *et al.* (2007) used a farm accounting approach to estimate the effect of nitrate reduction strategies on dairy farms in Ireland.

Unlike the aforementioned research this paper used microsimulation to provide estimations. In addition the marginal costs are calculated to compare the cost-effectiveness of the proposed strategies.

The paper is structured as follows: section 2 outlines different N mitigation strategies proposed in the literature and chosen for this analysis. Section 3 describes the data used for the analysis and relevant summary statistics are reported. The methodology is discussed in section 4, results are outlined in section 5 and conclusions are offered in section 6.

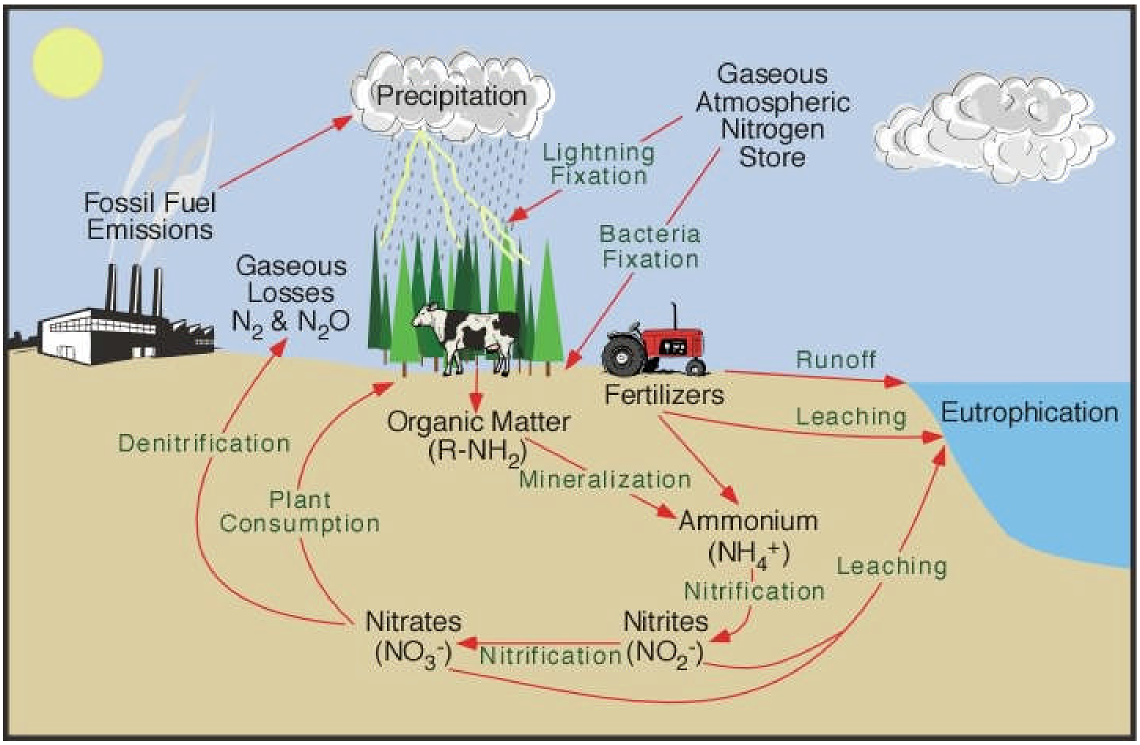
I.2 Background – Nitrogen losses from Agriculture

A wide range of policy options are available to policymakers to address undesirable losses of N from agriculture (Ritter, 2001, Novotny, 2003, Cuttle *et al.* 2006). The appropriate choice of mitigation strategies is closely connected to the N cycle in the environment. Thus understanding N movement and transformations in the environment and its interaction with agricultural systems in particular is important. The N cycle is complex and represents a network of different physical and bio-chemical pathways, and the pathways to surface and ground water are not well defined. A detailed outline and review of this cycle is beyond the scope of this paper (see Ritter, 2001; Merrington, 2002; Novotny, 2003 for more detail).

There are three main pathways through which different forms of N and its compounds circulate in the agricultural environment: inputs (into the soil), transformations (within the soil), and losses (out of the soil) (Merrington, 2002). Figure 1 illustrates an example of the N cycle and the N balance on an experimental farm in Ireland (Schulte, 2008).

The inputs of N occur through atmospheric depositions (rainfall), inorganic fertilizer application, organic manure application; mineralisation of the soil organic N; crop residue, and biological N fixation by legumes (National Research Council, 1993). Nitrogen exists in soil N in organic and inorganic forms. Most of the soil N is stored in the soil organic matter making it unavailable for plant uptake. Through the process of mineralisation and nitrification, organic N in soil and crop residue is transformed into ammonium (NH_4^+) and nitrate (NO_3^-), the forms that are available for plant uptake. There are a number of pathways through which N is lost from agricultural soil: plant uptake, volatilisation and denitrification, as well as losses through surface runoff and leaching to watercourses. The most beneficial pathway is plant uptake, however, nitrate is water soluble and excesses move readily in soil moisture (Ritter, 2001, Merrington, 2002, Novotny, 2003, National Research Council, 1993). All stages of the N cycle are dependent on a number of factors including geographical location of an agricultural enterprise, climate, underlying geology, soil permeability, soil microclimate and the type of agricultural enterprise (National Research Council, 1993).

Figure I.1. Nitrogen Cycle.



Source: (Pidwirny, M., 2006)

Both Fezzi *et al.* (2007) and Bateman *et al.* (2007) identify a number of key factors that encourage nitrate losses including over-fertilisation, high livestock numbers, excessive or poorly timed application of manure and exposure of bare soil during cultivation. N loss mitigation measures which address either excessive inputs or unwanted losses of N from agricultural activities to the wider aquatic environment are discussed extensively in the literature. Table 1 summarises the measures that are commonly proposed. Different issues and solutions are associated with each strategy.

When more chemical fertilizer is applied than is required by plants, the excess can potentially pollute the wider environment through losses to groundwater, surface streams and/or via overland runoff. Reduction of chemical fertilizer use can lead to the proportional reduction of the N introduced and quantities subsequently lost to the environment.

More precise application of organic fertilizer (both slurry and farm yard manures) as well as reducing livestock numbers is also possible options for reducing N in farm systems. Livestock, especially dairy cow, produce large volumes of manure as part of their lifecycle. This is either directly deposited to the land during grazing or is spread over the land after being stored.

DEFRA (2007) reports that most diets fed to livestock contain more N in the form of protein than is required by animals, consequently surplus N is excreted. Reduction of the N content of feed results in smaller amounts of N being excreted. Wright & Mutsvangwa (2003) report that switching from one feed to another can potentially reduce protein fed by 15-20 % yearly and will reduce N excreted by the animals proportionally. However, it involves urea N monitoring of milk, forage sampling as well as usage of high quality forages in order to achieve N reduction without adverse effects on animal health and milk quality.

Lalor *et al.* (2010) suggest that low utilisation of N in slurry can be attributed to the method and timing of application. More efficient application of slurry results in more N available in the manure/slurry and thus reduces chemical fertilizer requirements. Injecting the manure and slurry directly into the soil can reduce N losses through volatilisation and surface run-off, it also places the nutrients in the most biologically active part of the soil (Merrington, 2002). Precise calibration of the spreading equipment allows monitoring of the amount of fertilizer spread on each hectare.

Walsh *et al.* (2008) confirm that there is a difference in milk production potential between breeds of dairy cow. The breed with highest milk output, Holstein Friesian (HF), produces 4.2 % more milk than the average of other breeds. In Ireland over 95 % of the national dairy herd is Holstein Friesian. However, within the breed there is a wide variation in milk output, total solids, body condition score and fertility rates. The variation may be attributed to a better breeding index within the best performing herds. Increasing breeding index to achieve higher milk yields from dairy cows can potentially reduce the amount of N lost per unit of output.

Applying fertilizers near streams and/or allowing livestock to approach or enter watercourses can have a polluting effect. If these activities are restricted then the ecological pressure on streams can be reduced. Excluding animals from the areas next to the streams (fencing) can reduce the deposition of faecal material, turbidity from in-stream trampling and denudation of the stream banks. If fertilizer is not spread in the areas adjacent to streams, environmental gains are even higher. These areas may serve as filter strips as well (if enough vegetation is present), filtering runoff water from the rest of the field (Novotny, 2002). The costs associated with this strategy include: cost of fence construction, fence maintenance and a loss of grazing land (Ritter, 2001).

Wetlands have the potential to improve water quality as they can reduce the velocity of overland runoff; promote bacterial N removal; filter sediment and decrease nutrient loads. Novotny (2003) reports 50-80 % effectiveness in reducing N losses to water bodies. Ritter (2001) promotes wetlands as a cost-effective, efficient and suitable mechanism with the additional benefits of providing green space, habitats for wildlife as well as recreational areas. Similarly, riparian buffer zones and filter strips slow the overland transport of nutrients in runoff allowing more nutrients to be absorbed. The efficacy of this strategy depends on the width and type of vegetation present (Novotny, 2003).

Table I.1. N Loss Mitigation Strategies

Strategies	Related Issues	Solutions
Restricting Excessive Inputs		
Inorganic Fertilizer Reduction	Excess fertilizer applied to grassland can be lost to water through runoff and leaching.	Reduction of fertilizer application would help to avoid runoff & leaching of N from fertilizer excess.
Organic Fertilizer Reduction	Excessive and untimely application of manure/slurry causes N losses via volatilisation and/or runoff/leaching.	Reduction in organic fertilizer deposited and careful application reduces undesirable N losses.
Livestock Numbers Reduction	Livestock produce manure that is directly deposited to the land by animals during grazing or by land spreading of manures produced during the housing period.	Reduction in livestock units would reduce manure deposited and spread over land.
Change of Feed Mix	70-80 % of the ingested N is excreted by farm animals. The higher content of N in feed mix means higher N content in excreta.	Reduction of N in the diet allows to reduce N in animal excreta.
Calibration of Spreading Equipment/ injection vs overland spreading	More accurate and N efficient slurry application methods can improve the N fertilizer replacement value and decrease the farm N surplus by offsetting inorganic fertilizer N inputs.	Low ammonia emission application of slurry by optimising application timing and/or method.
Soil Testing	High risk of over-fertilising without testing the soil for the level of nutrients.	Early season soil testing reduces the risk of over-fertilisation.
Higher Performing Cattle breeds	The lower the yield of the dairy cow, the higher the N emissions per unit of output produced.	Utilisation of higher yielding cattle allows for reduction of the size of herd (excreta produced) without affecting output thus reducing N emissions per unit of output.
Reduction of N Losses		
Livestock exclusion (fencing off streams)	Manure deposition near/into streams causes water pollution. Allowing animals access to streams also causes sediment deposition and river bank destabilisation.	Prohibiting livestock access to streams prevents deposition of faecal material, turbidity and denudation of the stream banks.
Wetland Development/ Restoration	Overland runoff from agricultural land carries sediment and nutrients to streams.	Provides a filter for pollutants originating from agricultural land.
Riparian Buffer Zones/ Filter Strips	Overland runoff from agricultural land carries sediment and nutrients to streams.	Slows over-land runoff, allowing infiltration; allows nutrient uptake by vegetative cover.
Cover crops/ minimising periods when the soil is left bare	Leaving soil bare during the winter months and at cultivation increases risk of soil erosion and nutrient loss through runoff/leaching.	Cover crops provide protection against erosion, "green" manure source and additional revenue for farmers.
Timing of Fertilizer Application	Fertilizer application during/prior/straight after precipitation events or during autumn and winter leads to overland runoff or leaching of nutrients.	Timely fertilizer application prevents runoff/leaching, allows uptake of fertilizers by crops/grass.

There are a number of environmental and economic benefits of using cover crops after harvest. These include protection of the soil against erosion, prevention of nutrient losses, "green manure" for main crop, soil moisture management and a source of additional revenue for farmers (Ritter, 2001).

There are a number of enviro-economic dimensions of inefficient slurry management in terms of timing and method of application. When slurry/manure is managed inefficiently, more N is lost in the form of ammonia (NH_3) through volatilisation, creating unpleasant odours while increasing the requirement for chemical fertilizer. This increases the risk of N loss to the wider ecosystem with associated environmental cost and has an economic cost at farm level through lost nutrient to the farm system. Lalor *et al.*, (2010) report that the well-timed application of organic fertilizer can reduce undesirable losses of nutrients from agricultural land by increasing the fertilizer replacement value and reducing chemical N fertilizer inputs. Application of manure at times of low plant nutrient uptake can lead to losses of N through volatilisation, de-nitrification, leaching and erosion. Application of manure during the spring season yields optimal results, while autumn and winter applications are generally less optimal (Lalor *et al.*, 2010).

Eight nitrate mitigation strategies are considered in this paper. These strategies were selected for investigation in an Irish context as they are consistent with the theoretical literature (cited above) and with recommendations put forward in practical documents (DEHLG, 2010). These measures include: 1) chemical fertilizer reduction by 10%; 2) chemical fertilizer reduction by 20%; 3) livestock unit (LU) reduction to achieve a limit of 170 kg N ha^{-1}; 4) 20 % LU reduction; 5) change in feed mix to lower N feeds; 6) fencing off adjacent streams; 7) higher yielding dairy cows; 8) more efficient slurry application scenarios.

All the measures offer a potentially effective reduction of N losses (keeping other factors constant) from agricultural land. In addition a double-dividend may be achieved under some slurry application scenarios as there is a reduced N load available for transport to watercourses, while optimising farm production. However, the list of the proposed mitigation strategies is not exhaustive and a combination of strategies has also not been considered in this paper.

I.3 Methodology

Use of Marginal Abatement Cost Curves to assess the cost of pollution abatement

Ideally, policy makers should make decisions on the basis of economic efficiency. Cost-effectiveness is one criterion for selecting a pollution control instrument that is best for all types of pollution in all circumstances. A pollution abatement measure is cost effective if it attains a target at minimum cost. The Least Cost Theorem of pollution control states that a necessary condition for abatement at least total cost is that the marginal cost of abatement is equalised over all agents who undertake pollution control (Perman, 1999).

MAC methodology has gained popularity in recent years. It has been used by many researchers and policymakers in the environmental domain as an effective tool for policy assessment and to evaluate developments in agriculture, especially for green house gas (GHG) emissions and emissions trading (UNFCCC, 2007; McKinsey, 2007; Moran *et al.*, 2008). Where emissions trading schemes exist, MAC is the main tool used to calculate emission prices. It has also been used by environmental economists to aid in prioritising different investment decisions. MAC can also be used to estimate the cost of an overall emission mitigation target and show the most efficient way of reaching this target (Beaumont and Tinch, 2004). In the context of water quality, MAC is used to calculate the cost of different policy measures to reduce pollution from a number of sources. However, despite WFD demands for economic efficiency of resource allocation under a budget constraint, MAC is not widely used in the WFD policy-making arena. The main reason for this is a lack of enterprise and environmental data at a micro level that would allow calculations of specific cost functions as well as ecosystem damage functions.

Schulte *et al.* (2012) define a Marginal Abatement Cost Curve (MACC) as a graph that visualises the abatement potential of mitigation strategies and the relative cost associated with each strategy. The methodology used for estimation in this paper is based on the existing work by (Pearce and Turner, 1990 and Perman *et al.*, 1999) and has been adapted for the purpose of this research.

In order to be effective, a cost-effective environmental policy measure must possess a number of characteristics. First of all, and as has already been noted, marginal abatement costs (MACs) have to be equal across all abaters. Second, the agents with the lowest cost of abatement will undertake most of the abatement effort but not necessarily all of it. Third, in order to establish which measures are cost effective, the MAC of all polluters has to be known. In practice, however, the shape and the position of the marginal damage and MAC curves are extremely difficult to estimate. Thus, the least cost abatement will (as a rule) not lead to equal abatement effort by all agents. The theory tells us that uniform measures of pollution control will not lead to cost-efficiency of environmental protection.

MAC shows the extra unit cost of reducing the level of pollution by expenditure on abatement. It is assumed that MAC is convex, which implies that the lower the level of pollution, the higher the marginal cost of reducing it still further. It is based on empirical observation that it is comparatively cheap to eliminate or clean up the initial amounts of pollution but advanced forms of treatment, using chemicals or special filtering equipment may be required to eliminate or clean up very small amounts of pollutants (Pearce, 1990).

The conventional convexity assumption implies that, as a function of pollution, marginal damages are continuously increasing and marginal costs of abatement are continuously decreasing (Perman, 1999). However, in some cases MAC may not be convex, it may even be negative (e.g. some farmers may be over-fertilising, so reduction in fertilizer application would lead to reduction in costs without loss of output as well as reduction in environmental pressure).

In determining the MAC, it is necessary to know the values of marginal costs and marginal benefits of pollution abatement across the whole range of abatement possibilities (Perman, 1999). There are a number of caveats in using MAC for decision-making that have to be noted. First of all, defining the level of pollution on the basis of an economic efficiency criterion may not be acceptable in some cases. Other criteria should be considered including whether or not the "efficient" level of pollution poses threats to human or wildlife welfare. Secondly, the economically efficient level of pollution may not guarantee sustainability of resource use (Perman, 1999). In such cases safe minimum standards (SMS) may have a place. SMS criteria aim at eliminating polluting flows provided that doing so does not lead to excessive cost. SMS criteria can be designed to serve as a constraint on the efficiency decisions. This implies that in certain cases "correct" pollution levels cannot be worked out analytically. Expert judgements need to be made to identify situations where the efficiency-sustainability conflict exists and to decide what costs can be considered "excessive". The third caveat concerning the use of MAC is that the spatial dimension has to be considered.

Using farm-level MAC to assess the cost of nitrate mitigation strategies

Any optimal policy decision needs to be relevant on a micro as well as macro level, because the policy instrument that is cost efficient on a macro level may not be cost efficient for individuals. In the case of mitigating nitrate losses from farms, if each farms' abatement cost curve was known then each farm could stay below the farm emission threshold and thus stay within the aggregate emission target. According to the Least Cost Theorem, the aggregate emission ceiling could then be reached at the least cost. Alternatively, emission taxes or subsidies could be employed.

The estimation of farm-level MACC's requires knowledge of the effect of the proposed mitigation strategies on the production and cost functions of each farm as well as the amount of nutrient loss mitigated as a result of each strategy. As the system is non-linear, the changes in the production and the cost functions cannot be derived from ordinary least squares (OLS) regression coefficients, thus microsimulation is used in this case.

Microsimulation techniques have been widely used for many years and are an effective tool for evaluating socio-economic impacts of different policy options where it is difficult or impossible to conduct a real life experiment. Merz (1993) defines microsimulation in the following terms: "Simulation as one method of problem-solving becomes attractive when conventional analytic, numeric or physical experimental methods would be too time-consuming, expensive, difficult, hazardous and/or even impossible as real world experiments intended to solve a problem. Since economic and social real world systems in particular are hardly available as an experimental centerfield..."

There are two approaches that are used for calculating MAC: 1) "top-down" approach and 2) "bottom-up" approach. The "top-down" approach refers to general equilibrium models that usually take emissions as exogenous and estimate the cost of abatement at the macro level. In this paper the "bottom-up" approach is used. Through this approach the average cost of annual potential for individual N loss mitigation strategies is estimated at farm level. The ranking of the mitigation strategies then allows us to compare the results on the marginal steps of the curve (Blok *et al.*, 2001, Moran *et al.*, 2004, Beaumont and Tinch, 2004).

Microsimulation allows us to investigate the impact of different mitigation strategies on individual farm profit (π_i). This is the difference between the value of gross output (Y_i) less direct costs (C_i) and fixed costs (FC_i) (equation 1), where *i* denotes the individual farm. In Ireland many farms engage in more than one farm enterprise. Each enterprise is considered individually and the results are added together. The simple production and cost functions are estimated for three enterprises on dairy farms: dairy enterprise, cattle enterprise and sheep enterprise. Thus, six functions are estimated: dairy gross output, dairy direct costs, cattle gross output, cattle direct costs, sheep gross output, and sheep direct costs (equations 2 and 3).

The functions are estimated in log-polynomial ordinary least squares (OLS) regressions (equations 2 and 3). OLS has been chosen as the error term exhibits a normal distribution. X_{ij} is a vector of explanatory variables such as livestock units, farm size, fertilizer usage and concentrates. These variables determine the level of each enterprise gross output (Y) and direct costs (C), where *j* denotes dairy, cattle or sheep enterprise on the farm.

$$\pi_i = Y_i - C_i - FC_i \qquad (1)$$

$$Y_{ij} = \beta_j X_{ij} + \varepsilon_{ij}^{y} \qquad (2)$$

$$C_{ij} = \gamma_j X_{ij} + \varepsilon_{ij}^{c} \qquad (3)$$

Knowledge about the relationship between dependent and explanatory variables allows us to simulate the effect of the proposed mitigation strategies by holding the regression coefficients (β, γ) and the error terms (ε_{ij}^{y}, ε_{ij}^{c}) constant and changing the explanatory variables according to the different strategies.

When the parameters of the model are estimated the new production and cost functions are simulated (denoted as X^S, C^S, Y^S). In the Where there is additional expenditure associated with mitigation strategies, this is also estimated. The impact of the simulated changes in the animal numbers and/or fertilizer is the difference between farm income before and after the change (equations 4, 5 and 6).

$$\Delta\pi = \pi^S - \pi \qquad (4)$$

$$\pi = Y - C - FC \qquad (5)$$

$$\pi^S = Y^S - C^S - FC^S \qquad (6)$$

The amount of total N produced on the farm depends on the number of livestock units and the amount of chemical fertilizer used as a part of the production process. The changes in N arise from the change in animal numbers and chemical fertilizer quantity (equations 7 and 8) according to individual strategies.

$$N = f(animal\_numbers, fertiliser) \qquad (7)$$

$$\Delta N = N - N^S \qquad (8)$$

$$MAC = \Delta N / \Delta\pi \qquad (9)$$

The MAC is the change in total N per unit change in farm profit (9). The micro data used in this analysis and the microsimulation strategies employed allow us to not only rank the MAC's on the aggregate level but on the micro-level as well. This makes it possible to compare the MAC curves across individual farms.

I.4 Data

The Teagasc National Farm Survey (NFS) is the principal data source used in this analysis. NFS data have been collected on an annual basis by Teagasc (The Irish Agriculture and Food Development Authority) since 1972. The NFS contains a nationally representative sample of approximately 1,200 farms. It excludes pigs and poultry farms due to inability to obtain a representative sample for these types of farms as farming in Ireland consists of predominantly ruminant farming. The NFS dataset is particularly useful for our analysis as it contains socio-economic information which allows for analysis of the physical and economic performance of different farming sectors. It also allows for the derivation of relevant variables e.g. organic and chemical N produced and used in the farm system. Geographic Information Systems (GIS) data regarding the length of the streams and the proportion of the farm land within the streams were also obtained specifically for the purpose of this paper.

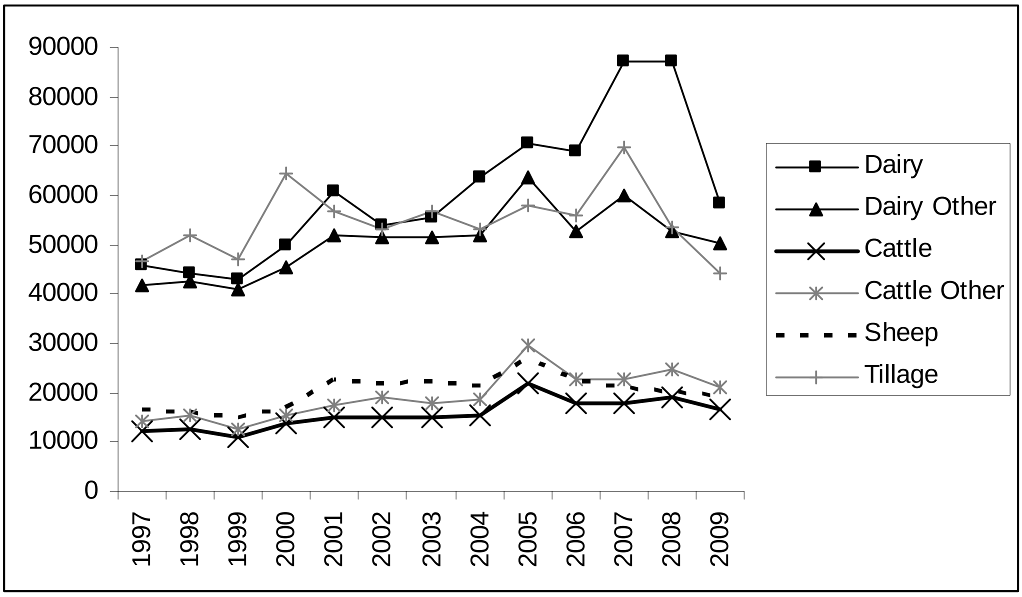
In this paper NFS 2008 data are used despite the fact that more recent NFS 2009 data are available to the authors. The main reason for this is that 2009 was an exceptionally bad year for Irish farmers as gross margins on Irish farms declined by almost 20 % compared to 2008. Most of the decline was due to a fall in gross output from €55,674 to €47,953. At the same time gross margins for dairy producers fell by almost 26 % - from €75,489 in 2008 to €55,929 in 2009. The unusual nature of the decline in 2009 meant that it was "not representative" from a modelling perspective.

Farms in the NFS are assigned to one of six possible systems: 1) specialist dairy; 2) dairying other; 3) cattle rearing; 4) cattle other; 5) mainly sheep; 6) mainly tillage. Category assignment is based on the dominant enterprise established using Standard Gross Margins (SGMs) under the EU Farm Accountancy Data Network (FADN) typology set out in the Commission Decision 78/463 (Hynes *et al.* 2008). Farms in Ireland typically engage in a number of enterprises, which make it more difficult to differentiate between systems and makes modelling more complex as it can be difficult to distinguish between resources used for different enterprises (the dairy enterprise variables in NFS are given as an example in Apendix 1). The number of farms in the NFS sample varies from year to year ranging from 1,279 farms in 1994 to 1,054 in 2009, reflecting the decreasing number of farms in Ireland. Specialist dairy and dairy other farms comprised 33 % of the NFS sample in 2008. National weights are applied to represent the entire population of farms in Ireland. National weights are produced by Teagasc on the basis of the Census of Agriculture tables produced by the Irish Central Statistics Office (CSO). All summary statistics and model results reported in this paper are produced on the basis of weighted NFS data.

For the purpose of our research we are focussing on farms that are identified in the NFS as "specialist dairy" and "dairy other". There are two primary reasons for focusing on dairy farms: 1) the relative economic importance of the dairy sector and 2) dairy and dairy other farms are likely to expand production once quota restrictions are lifted in 2015, in order to meet the 50 % productivity targets specified in the government's Food Harvest 2020 strategy (DAFM, 2010). In terms of economic significance, dairy farms in Ireland have higher gross margins than other farm systems. Their output has been increasing since 1999 (see Figure 2). Gross Margin (GM) is a good indicator of the performance of farms because it represents the difference between Gross Output (GO) and Direct Costs (DC) and allows us to understand performance differences within enterprises and/or systems on Irish farms. However, relative movements in GO and DC provide useful information about the source of change in GM. For example, a sharp dip in dairy and cattle gross margins between 2008 and 2009 was due to an abrupt fall in output (price driven), while the direct costs stayed relatively unchanged.

It is evident (Figure 2) that dairy and dairy other farms have a significantly higher GM than cattle, cattle rearing and mainly sheep farm systems. It is also clear that dairy GM was growing at a higher rate than other systems and experienced a sharper fall in GM between 2008 and 2009.

Figure I.2. Dynamics of Gross Margins on farms in Ireland (1997-2009)



(Source: NFS data – multiple years)

Dairy and dairy other farms are not only leaders in economic performance, but they also have higher organic N production and chemical N use (Table 2) relative to other systems. The national average (which is lower than the non-derogation requirement of

170 kg organic N ha^{-1} under SI 378 of 2006) disguises the range of fertilizer application across Irish farms. In the NFS sample, organic N per hectare levels are as high as 247 kg ha^{-1} while the highest amount of chemical N applied is 395 kg ha $^{-1}$.

Table I.2. Mean N production and percentage of farms in N production categories, 2008

Org. N (kg ha^{-1})				Chemical. N (kg ha^{-1})			
Farm System	<170	>170	Mean	<226	226-279	>279	Mean
Specialist dairy	79%	21%	142	92%	5%	3%	134
Dairy other	96%	4%	82	99%	1%	0	67
Cattle	99%	1%	72	100%	0	0	40
Cattle rearing	99%	1%	79	100%	0	0	42
Sheep	100%	0	36	100%	0	0	36
Tillage	100%	0	22	78%	1%	21%	62

(Source: NFS data)

Specialist dairy farms produce and use on average almost twice as much of organic and chemical N as any other system. Dairy other farms, despite reducing N emissions in the last few years, still produce higher amounts than other systems. As defined by SI 378 of 2006 the maximum non-derogation production of organic N is limited to 170 kg N ha^{-1}. In 2008, 21% of the dairy farms in Ireland exceeded this limit (Table 2). These farmers currently have the option to apply for a derogation to apply up to 250 kg N ha^{-1} or to export the excess manure.

In order to estimate the effect of the stream fencing scenario, information on the number of farms that have streams within 500 meters of the farmhouse was collected. GIS was used to collect these data. Data on the proportion of farmland within a 1m, 5m, 10m, 15m, 25m and 50m buffer were also obtained.

I.5 Nitrate Loss Mitigation Strategies[1]

In order to formalise the model, certain assumptions had to be made within each strategy. In the fertilizer reduction scenarios the volume of chemical fertilizer used on dairy farm is reduced by 10 % and 20 % respectively. The model also aims to allow for realistic managerial decisions wherever possible. In reducing livestock numbers on a

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[1] From this point onwards, dairy and dairy other farms will be referred to collectively as dairy farms

mixed farm, it is assumed that the farmer will first reduce numbers in the livestock enterprise with the lowest gross margin.

While Whrite and Mutsvangwa (2003) suggest possible lowering of feed costs as a result of using more efficient N feed, in this analysis it is assumed (in line with DEFRA, 2007 and Fezzi *et al.*, 2007) that there is an extra cost associated with this strategy. In the model a 25 % increase in the cost of new feed mix is assumed. This cost is associated with the higher price of new feed and protein monitoring. The 15 % decrease in the production of inorganic N is in line with the findings of Whrite and Mutsvangwa (2003).

In order to estimate the effect of fencing off streams, introducing higher yield dairy cows and the efficient slurry application, additional data and calculations were necessary before simulation could be undertaken. GIS data are used to determine the length of fencing required to fence off streams adjacent to the dairy farms. The cost of the fencing includes the actual cost of erecting the fence of €0.90 per meter (Hynes *et al.*, 2008, Chyzheuskaya *et al.*, forthcoming) and the cost associated with the reduction in productive land area. Ten metre zones are assumed to be fenced off. Two possible sub-scenarios are estimated: 1) the possible intensification of production where farmers would keep the existing livestock numbers despite the reduction in overall farm size; and 2) a reduction in production intensity, where a farmer would choose to reduce the number of LU pro rata based on the reduction in farm size. The land taken out of production is assumed to be pasture or forage land on the dairy farm. This scenario will lead to a reduction in fertilizer used on the land taken out of production (in cases where farmers choose to reduce the livestock numbers). In the case of intensification of production there will be an increase in costs associated with extra chemical fertilizer spread on pasture in order to ensure sufficient grass production. If the latter happens the change in N could potentially be in the opposite direction to environmental policy objectives as there will be an increase in both organic and chemical N ha^{-1}. Increases in organic N per unit area will result from an increase in stocking rate due to a decrease in land available for spreading slurry. Increases in chemical N may result if more fertilizer is needed to ensure sufficient grass cover for increased stocking rate due to loss of area.

There are a number of factors affecting milk output per cow: breeding index, parity, season of calving, geographic location, management factors (feed, milking intervals, milking frequency) (Diskin, 2012). Improving the breeding index within dairy herds can significantly improve the milk output per cow allowing a reduction in herd size and consequently a reduction in N produced on the farm.

Data on breeding indices are currently not available within the NFS dataset. The effect of increasing milk yield by improving breeding index is estimated through regressing the average yield per cow in the dairy herd (Q), on the amount of concentrates, number of days grazed, early/late calving and predicting the error term ε (as set out in (10)). This captures the variation in milk output due to the breeding index. The lowest average yield in the top yield per cow quintile is taken as the yield target, and the error term associated with it is substituted instead of the error terms in the lower yield quintile regressions and the new milk yield per cow is predicted. This allows for a reduction of the herd size without the loss of production. The size of the new reduced dairy herd is calculated and the effect of the reduction on direct costs, gross margin and N reduction is estimated through microsimulation as outlined in section 3.

$$Q = F(X) + \varepsilon \qquad (10)$$

There are extra costs associated with this strategy including additional feed for higher yield cows. This is assumed to be offset by the reduction in the herd size and the cost of increasing breeding index (artificial insemination straws and labour), which is costed at 4.5 artificial insemination (AI) straws per cow at a total cost of €20 per straw (Diskin, 2012).

One strategy that can potentially allow the decrease of chemical N usage on the farms is increasing the N efficiency from applied cattle slurry by improving the timing and method of application. Lalor *et al.* (2010) report that the method of application and the timing of application both affect the utilisation of N by grass due to variation in N losses through NH_3 volatilisation. By optimising both application method and timing, the N fertilizer replacement value (NFRV) can be increased, resulting in a reduction in the chemical N fertilizer requirement on the farm. This has the effect of reducing the overall N surplus on the farm, and hence decreasing potential N losses.

It is reported that 34 % of slurry is spread by farmers during spring and about 50 % during the summer and the remainder (16 %) is spread in autumn using mainly the splash-plate (SP) method of application (Hyde *et al.*, 2006). The availability of slurry N in summer and autumn is similar, hence it is assumed in this paper that 66 % of slurry is spread during the summer. Each tonne of slurry contains approximately 3.6 kg of N. However, the N availability from slurry differs depending on the timing of application and method of application (Table 3). The trailing shoe (TS) method of application increases N availability in slurry by 10 percentage points both in summer and in spring. By switching both the time and method of slurry application, the benefits of both application timing and method are additive (Lalor *et al.*, 2010).

Table I.3. N availability in slurry with respect to time & method of application

Method	Splash-plate		Trailing Shoe	
Timing	Summer	Spring	Summer	Spring
Total N content (kg/m^3)	3.6	3.6	3.6	3.6
NFRV %	12%	21%	22%	30%
Available N in slurry (kg/m^3)	0.43	0.76	0.79	1.08
N chemical fertilizer advice per cow at stocking rate of 2 LU/ha (kg ha^{-1})	100.5			
Slurry production per cow (m^3 in a 16 week winter period)	5.3			

Three slurry application sub-scenarios are estimated: 1) switching to slurry application in spring *vs* summer without changing the method of application; 2) changing the method of application without changing the time of application; 3) changing both time and method of application.

A dairy cow produces 5.3 m^3 of slurry in 16 weeks of housing (SI 378 of 2006), which contains approximately 19 kg of N. In a summer application only 12 percent of this is available for crop/grass uptake, and in a spring application 21 % is available. The demand for chemical N fertilizer depends on farm stocking rate, e.g. at the stocking rate of 2 LU Ha^{-1}, in the absence of slurry application, 100.5 kg/cow of chemical N fertilizer would be required as advised by Coulter and Lalor (2008). If 66 % of slurry is spread during the summer and 34 % in spring (at the aforementioned stocking rate) 97.63 kg per cow of chemical N fertilizer is required instead of 100.5 kg.

Under scenario 1, if 100% of slurry is spread in spring, at 4.0 kg of available N per cow from slurry, the amount of chemical N required can be reduced to 96.5 kg. Under scenario 2, using the trailing shoe (TS) application method (assuming no change in seasonal application pattern) results in 4.7 kg N available per cow and the demand for inorganic N fertilizer is reduced to 95.8 kg. Under Scenario 3, switching from splash-plate (SP) application in summer to trailing shoe application in spring results in additive benefits, and reduces the chemical fertilizer N requirement to 94.8 kg per cow.

Switching from summer to spring application has no extra cost and is only constrained by soil trafficability conditions. There is an extra cost of €0.77 per m^3 (Lalor, 2008) associated with using TS machinery instead of SP. This amounts to an extra cost of €4.08 per year per cow for TS application. The N fertilizer savings per cow are highly dependent on the stocking rate of the farm, and will vary depending on the fertilizer N advice for the farm, which is mainly influenced by stocking rate. Thus chemical N fertilizer requirement and cost associated with each strategy is calculated for each farm according to stocking rate. The change in costs is calculated as the difference between the chemical fertilizer reduction and extra cost associated with hiring TS machinery instead of SP machinery.

I.6 Results

Estimates for Model

Estimates for higher yield dairy cows scenario

Because the breeding index of the dairy cattle is not included in NFS data, it had to be estimated in OLS (Ordinary Least Squares) regression, where breeding index constitutes part of the residual. The results of OLS estimations for the higher yielding dairy scenario are reported in Table 4. The dependent variable is the log of milk output in litres per dairy cow produced on the farm. The independent variables used (constrained by data availability) include kilograms of concentrates per dairy cow and its square term; an early calving dummy variable, which takes a value of 1 for farms that have 80 % or more calves born in January, February and March, and a value of 0 for the rest of farms; and calves per cow and its square term.

Table I.4. Results of "Higher Yield Cattle" Estimations.

Ln(milk output/LU)	β	St. Error	T	P
Concentrates/LU	.0002815	.0000273	10.33	0.000
$(\text{Concentrates/LU})^2$	-1.96e-08	2.32e-09	-8.42	0.000
Early Calving	.0720532	.0253178	2.85	0.005
Calves/LU	.4323881	.2836411	1.52	0.128
$(\text{Calves/LU})^2$	-.1711034	.1112484	-1.54	0.125
Constant	7.973482	.1751493	45.52	0.000

R-squared = 0.2612   Adj R-squared = 0.2496

The explanatory power of the regression is not very high as there are a number of variables that are omitted from the regression due to data limitations. The variable number of calves per cow, proved to be statistically insignificant but was retained in the regression as a proxy for cow fertility.

Estimates for Production and Cost Functions

The production and cost functions were estimated for each enterprise on the farm. The model was developed for specialist dairy and dairy other farms - some outlier farms had to be removed from the data. All the variables used for estimations are enterprise-specific, unless specified otherwise. The shape of the production and cost functions was estimated on the whole population of farms in the NFS sample as the significance of some variables was lost when the model was run using dairy farms only.

The results of the production function for dairy, beef and sheep enterprises on NFS dairy farms weighted to the population are reported in Table 5 and results of the cost function for dairy, beef and sheep enterprises are reported in Table 6. Concentrates and fertilizer usage are the main drivers of both production and costs on grass-based dairy farms in Ireland. The variables size of farm and number of livestock units are included in the model to account for economies of scale. Other costs mainly relate to enterprise specific expenses such as routine veterinary checks/treatments and expenses on artificial insemination.

Table I.5. Results for Dairy Farms Production Function Estimations

Dairy Enterprise			Beef Enterprise			Sheep Enterprise		
Ln(GO/LU)	β	St. Error	Ln(GO/LU)	β	St. Error	Ln(GO/LU)	β	St. Error
Winter forage/LU	-.0004912	.0002735	Number of LU	-.0041386	.001467	Number of LU	-.0041555	.0235157
Other costs/LU	.001092	.0003044	Fertilizer/LU (€)	.0010192	.0005917	Forage Area	.022305	.0169521
(Other costs/LU)^2	-1.37e-07	3.50e-07	Concentrates/LU	.0011881	.0004619	Size of farm	-.0210611	.0217434
Concentrates/LU	.000363	.0000924	Other costs/LU	-1.34e-07	9.31e-07	Size of farm^2	.0000308	.000101
Number of LU	.0001106	.0015353	(Other costs/LU)^2	4.00e-07	1.12e-07	Fertilizer (kg)	-.0000453	.0003729
(Number of LU)^2	-7.24e-06	7.07e-06	Forage area	.0022501	.0018901	Fertilizer (kg)^2	1.94e-08	4.90e-08
Size of farm	.0003639	.0010707	Forage area^2	9.13e-06	.0000123	Constant	5.83391	.617836
(Size of farm)^2	2.94e-06	5.09e-06	Size of farm ^{2}	-6.04e-06	9.00e-06			
Fertilizer	.0000458	8.47e-06	Fertilizer (kg)	.0000285	.0000174			
Fertilizer ^{2}	-1.24e-09	2.98e-10	Fertilizer (kg)^2	-4.06e-10	5.58e-10			
Constant	6.838433	.0673511	Constant	6.082069	.1000011			

Table I.6. Results for Dairy Farms Cost Function Estimations

Dairy Enterprise			Beef Enterprise			Sheep Enterprise		
Ln(DC/LU)	β	St. Error	Ln(DC/LU)	β	St. Error	Ln(DC/LU)	β	St. Error
Winter forage/LU	.0001613	.0000894	Number of LU	-.0033862	.0003783	Number of LU	-.0279572	.0129214
Other DC/LU	.0020734	.0001006	Concentrates/LU	.0029819	.0001233	Concentrates	.0001841	.0000434
(Other DC/LU)2	-1.08e-06	1.16e-07	(Concentrates/LU)^2	-2.38e-06	2.48e-07	Winter forage	.0002172	.0003834
Concentrates/LU	.0025038	.0000851	Other DC/LU	.0024576	.0000899	Size of farm	-.0047472	.0082147
(Concentrates/LU)^2	-1.47e-06	1.17e-07	(Other DC/LU)^2	-8.19e-07	7.07e-08	Size of farm ^{2}	.0000277	.0000468
Number of LU	-.0046304	.000502	Fsizfrac	-.0009685	.0004931	Fertilizer (kg)	.0005661	.0001817
(Number of LU)^2	.0000101	2.31e-06	Fsizfrac2	-1.52e-06	3.39e-06	Fertilizer (kg)^2	-8.39e-08	2.56e-08
Size of farm	.0004688	.0003502	Size of farm^2	9.14e-06	2.32e-06	Constant	4.976742	.2802786
Size of farm^2	5.75e-07	1.66e-06	Fertilizer (kg)	.0000452	3.80e-06			
Fertilizer (kg)	.0000366	2.78e-06	Fertilizer (kg)^2	-8.97e-10	1.38e-10			
Fertilizer (kg)^2	-7.66e-10	9.78e-11	Constant	5.226381	.0271676			
Constant	5.390613	.0232737						

Simulated Results

Gross margin analysis of mitigation strategies

Results for farm GM ha^{-1}, enterprise GM, GO and DC under the baseline and each proposed policy are summarised in Table 7 below. Gross Margin ha^{-1} declined on average for the subset of affected farms under most of the strategies with the exception of the higher yielding cows for which the GM per hectare increased from €1,199 to €1,270 and slurry application scenarios under which farm GM increases from €1,314 to €1,319, €1,315, €1,318 ha^{-1} respectively. The overall trend reflects the fact that the proposed mitigation strategies will generally affect either the size of production or will increase the costs of production resulting in lower gross margin on the dairy farms. Only the strategies that increase production and/or cost efficiency yield positive economic results.

Table I.7. Farm and enterprise GM, GO, DC under each mitigation strategy

Scenario	GM	DGM	DGO	DDC	CGM	CGO	CDC	SGM	SGO	SDC
Baseline	1314	55786	89709	33922	7685	24698	17013	308	676	369
Fert -10%	1297	54965	88590	33625	7846	24450	16604	233	651	418
Fert-20%	1278	53981	87325	33344	8009	24208	16199	159	631	471
Reduce LU -20%	1037	44638	72137	27499	5845	20841	14996	192	555	363
Feed change	1239	52365	89709	37344	7685	24698	17013	308	676	369
Slurry 1*	1319	55786	89709	33922	7685	24698	17013	308	676	369
Slurry 2**	1315	55786	89709	33922	7685	24698	17013	308	676	369
Slurry 3***	1318	55786	89709	33922	7685	24698	17013	308	676	369
Baseline	1792	68818	113394	44577	5750	26399	20649	168	247	79
Feduce LU 170kg	1680	67793	111817	44024	2631	13517	10886	168	247	79
Baseline	1324	55409	89035	33627	7462	24152	16690	276	626	350
Fencing-off (intensif)	1321	55326	88938	33613	7514	24229	16714	288	638	350
Fencing-off (de-intensif)	1280	53960	86794	32834	7345	23767	16423	258	621	363
Baseline	1199	47458	75715	28258	7172	22513	15341	356	784	429
Higher yield cows	1270	50805	75715	24910	7172	22513	15341	356	784	429

*change in the timing of slurry application to spring;
**change the method of slurry application from SP to TS;
*** change the timing and method of slurry application.

The highest negative impact is observed under the reduce LU by 20 % scenario, when farm GM ha^{-1} drops by €277 from €1,314 to €1,037. There is a loss of gross margins across all enterprises. When the target is to reduce organic N emissions down to 170 kg N ha^{-1}, the farm GM on the affected farms would decline on average by €4,237, or by €112 ha^{-1}. This strategy is more likely to affect more intensively producing farms with the stocking rates close to or over two LU per hectare and a higher average farm GM. Under this scenario mostly cattle gross output (CGO) and direct costs (CDC) are projected to fall on average by €12,882 and €9,763 respectively leading to a reduction in the beef GM of €3,119 on average dairy and dairy other farms. The underlying assumption is that the farmers would drop the livestock with the lowest GM per animal. Results from the NFS sample in 2008 indicate that cattle LU attract on average lower GM returns on dairy and dairy other farms in Ireland.

Feed change would lead on average to a loss of €75 per hectare this is due to assumed increase in feed cost which would drive the direct costs on the farms. Reducing fertiliser by 10% or 20% would lead to a loss of €27 and €36 per hectare respectively. Fencing off streams would result in a loss of €44 per hectare on affected farms if the farmers reduced stocking rates proportionally to reduction in farmed land. However, if the farmers decided to keep their stocking numbers and intensify the production on the remaining land the loss would be mostly offset down to €3 per hectare. However, this may mean that environmental objectives would not be met.

Table I.8. Percentage change in farm and enterprise GM, GO, DC under different N loss mitigation strategies, %

Scenario	GM	DGM	DGO	DDC	CGM	CGO	CDC	SGM	SGO	SDC
Baseline										
Fert -10%	-1.3	-1.5	-1.2	-0.9	2.1	-1.0	-2.4	-24.3	-3.8	13.3
Fert-20%	-2.8	-3.2	-2.7	-1.7	4.2	-2.0	-4.8	-48.2	-6.7	27.8
Reduce LU -20%	-21.1	-20.0	-19.6	-18.9	-23.9	-15.6	-11.9	-37.5	-18.0	-1.7
Feed change	-5.7	-6.1	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0
Slurry 1*	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slurry 2**	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slurry 3***	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Baseline										
Reduce LU 170kg	-6.2	-1.5	-1.4	-1.2	-54.2	-48.8	-47.3	0.0	0.0	0.0
Baseline										
Fencing-off (intensif)	-0.2	-0.1	-0.1	0.0	0.7	0.3	0.1	4.3	1.9	0.1
Fencing-off (de-intensif)	-3.3	-2.6	-2.5	-2.4	-1.6	-1.6	-1.6	-6.6	-0.8	3.7
Baseline										
Higher yield cows	5.9	7.1	0.0	-11.8	0.0	0.0	0.0	0.0	0.0	0.0

*change in the timing of slurry application to spring;
**change the method of slurry application from SP to TS;
*** change the timing and method of slurry application

Table 8 reports the percentage change in GM, GO and DC as a result of simulated mitigation strategies. Farm GM per hectare falls under all strategies except under the higher yielding cow strategy, which on average led to an increase in GM per hectare of 5.9 % on affected farms and the slurry scenarios which on average led to a small increase in farm GM per hectare. The smallest decrease in the farm GM per hectare was estimated under the fencing off (intensification of production) scenario at 0.2 %, which was due to a fall in the dairy enterprise GO by 0.1 % leading to the 0.1 % reduction in DGM.

The largest decline in farm GM per hectare is observed under the 20 % LU reduction scenario, where the farm GM per hectare dropped by 21 %. This mitigation strategy, as can be seen in Table 8, would negatively affect all farm enterprises (dairy, cattle, sheep) on predominantly dairy farms and would lead to falls in DGM, CGM and SGM of 20 %, 24 % and 37 % across these enterprises respectively.

If farmers were to use more efficient feed in an effort to decrease N excreted by the dairy cattle, they would experience on average 6.1% decline in the dairy enterprise GM, due mainly to a 25 % increase in associated feed costs. However, because the data on the costs of using lower protein feeds are not available from real life experiments, the results under this scenario should be interpreted with care.

Reducing LU ha^{-1} to achieve 170 kg organic N ha^{-1} results in a decrease in the farm GM per hectare of 5.21 % on the affected farms. This arose due to a fall in the beef enterprise GM and dairy enterprise GM (Table 8). This is despite the fall in costs. The results also revealed that not all the farms that exceed the 170 kg of organic N ha^{-1} are equally affected. In the NFS data sample weighted to represent national farm population, 22 % percent of dairy and dairy other farms exceed the limit. If they were to reduce emissions to comply with the stated limit, around 90.5 % of these farms would have a loss of GM and 9.5 % would have a gain in GM due to the fact that on some farms beef cattle attract a zero or even negative GM. In our study on the 2008 NFS data, 8.9 % of affected farms would lose over 30 % of their farm GM; 7.6 % would lose between 20 and 30 % of the farm GM and 58 % of affected farms would lose between 10 and 20 % of farm GM.

Increasing the breeding index of dairy cows in order to produce higher milk yields per dairy cow and the subsequent reduction in the herd size produces a 7.1 % increase in dairy enterprise GM due to the direct cost reduction of 11.8 % associated with the reduction in animal numbers and associated costs. There is an extra cost associated with this strategy, which includes the cost of 4.5 AI straws per cow plus extra labour and is assumed to be €20 per straw over 5 years. The results of this scenario should be interpreted with the most care as a lot of assumptions were made during modelling.

Table I.9. Effect of the N Mitigation Measures on Farm Net Margin and Farm Net Margin per hectare

Scenario	FNM/ha	FNM
Baseline	441.45	21081.66
Fert -10%	424.43	20346.58
Fert-20%	405.22	19452.57
Reduce LU -20%	164.47	7977.58
Feed change	366.63	17659.88
Slurry 1*	444.24	21235.07
Slurry 2**	440.85	21074.99
Slurry 3***	443.97	21222.89
Baseline	625.70	25620.62
Feduce LU 170kg	514.05	21477.08
Baseline	427.33	20287.08
Fencing-off (intensif)	405.93	20227.08
Fencing-off (de-intensif)	365.47	18395.61
Baseline	376.47	17115.45
Higher yield cows	447.29	19612.12

*change in the timing of slurry application to spring;
**change the method of slurry application from SP to TS;
*** change the timing and method of slurry application

Sometimes the farmers are concern to see how the mitigation measures would affect the Farm Net Margin (FNM) rather than GM. The effect of the measure on the FNM is reported in Table 9. The effect on FNM and FNM per hectare is more dramatic that on the GM. The reduction in LU by 20 % would lead to FNM reduction from €441.45 per hectare to €164.47 per hectare and an average FNM loss of more than €13,000. Reducing LU to achieve 170 kg of N ha^{-1} would lead to a FNM loss of over €4,000 and fencing off stream would lead to a loss of €1890 on average per farm. Higher yield cows would lead to gain in the FNM, however, the initial investment could be high.

Farm nitrogen implications of mitigation strategies

Table 10 summarises the amount of organic, chemical and total N produced on the affected farms under each strategy and the percentage changes. All strategies produce a reduction in total N (except for the case of intensification of production after fencing off streams), however, some strategies produce larger total N reduction than others. Over 12 % of total N can be abated by cutting chemical N fertilizer usage by 20 %. Relatively high total N reduction can also be achieved by reducing chemical N fertilizer application by 10% and decreasing the number of LU by 20%, 6% and 7.9% respectively. Increasing the breeding index of dairy animals would allow farmers to abate 3.9 % of total N on affected farms. Under the LU reduction to 170kg N ha^{-1} strategy, on average 17.7 % organic N can be mitigated. However, the cost of abating N under the different strategies varies across farms. This will be discussed in the following sections.

Table I.10. N production under different strategies

Scenario	OrgN		ChemN		TotalN	
Baseline	143.8	-	220.1	-	363.9	-
Fert -10%	143.8	0.0%	198.1	-10.0%	341.9	-6.0%
Fert-20%	143.8	0.0%	176.1	-20.0%	319.9	-12.1%
Feduce LU 170kg	136.0	-5.4%	220.1	0.0%	356.1	-2.1%
Reduce LU -20%	115.0	-20.0%	220.1	0.0%	335.1	-7.9%
Slurry 1*	143.8	0.0%	218.7	-0.6%	358.4	-1.5%
Slurry 2**	143.8	0.0%	217.0	-1.4%	362.5	-0.4%
Slurry 3***	143.8	0.0%	215.8	-2.0%	360.8	-0.8%
Feed change	122.8	-14.6%	220.1	0.0%	342.9	-5.8%
Baseline	199.25	-	307.00	-	506.25	-
Feduce LU 170kg	163.94	-17.7%	307.00	0.0%	470.94	-7.0%
Baseline	142.55	-	223.43	-	365.98	-
Fencing-off (de-intensif)	139.33	-2.3%	218.48	-2.2%	357.81	-2.2%
Baseline	142.28	-	208.58	-	350.86	-
Higher yield cows	128.61	-9.6%	208.58	0.0%	337.19	-3.9%

*change in the timing of slurry application to spring
**change the method of slurry application from SP to TS;
*** change the timing and method of slurry application

MAC Results

The changes in economic and/or nitrogen generation at farm level as reported in Tables 7 – 9 do not in themselves allow cost-efficiency comparisons. Marginal abatement costs for each strategy are calculated (except for intensification of farming due to fencing off streams) and reported in Table 11 below to examine policy scenario effectiveness. The results represent the cost in € per kg of nitrogen abated ha^{-1}, ranging from a cost of over €10 per kg N ha^{-1} for the fencing-off (de-intensification) strategy to a saving of €3 per kg N ha^{-1} for the improved cow breeding index strategy as outlined in Table 11.

Table I.11. Marginal Abatement Cost

Mitigation Strategy	Cost (€ per kg N Ha^{-1})
MAC Fert -10%	0.76
MAC Fert-20%	0.79
MAC Reduce LU 170kg	3.40
MAC Reduce LU -20%	9.51
Feed change	3.56
Fencing-off (de-intensif)	10.10
Slurry 1*	-2.50
Slurry 2**	-0.03
Slurry 3***	-0.74
Higher yield cows	-3.00

*change in the timing of slurry application to spring;
**change the method of slurry application from SP to TS;
*** change the timing and method of slurry application

The higher the positive MAC result the more expensive it is to abate each unit of total N for farmers (Table 11). The negative sign of the MAC for slurry scenarios and higher yielding cows indicate that these strategies on average would not only produce a decrease in total N introduced into the environment but would also lead to a reduction of costs on farms.

The ranking of the marginal abatement costs of each mitigation strategy is presented in Figure 3. Changing the timing/method/both of slurry application and increasing breeding index of the dairy herd are the most cost-efficient results for N abatement. However, further investigation revealed that country average MAC numbers hide the diversity of impacts that each strategy would have across individual farms in the sample. Figure 4 shows MAC curves for each strategy for all the individual dairy farms in the NFS.

Figure I.3. Aggregate MAC for dairy farms across all farms

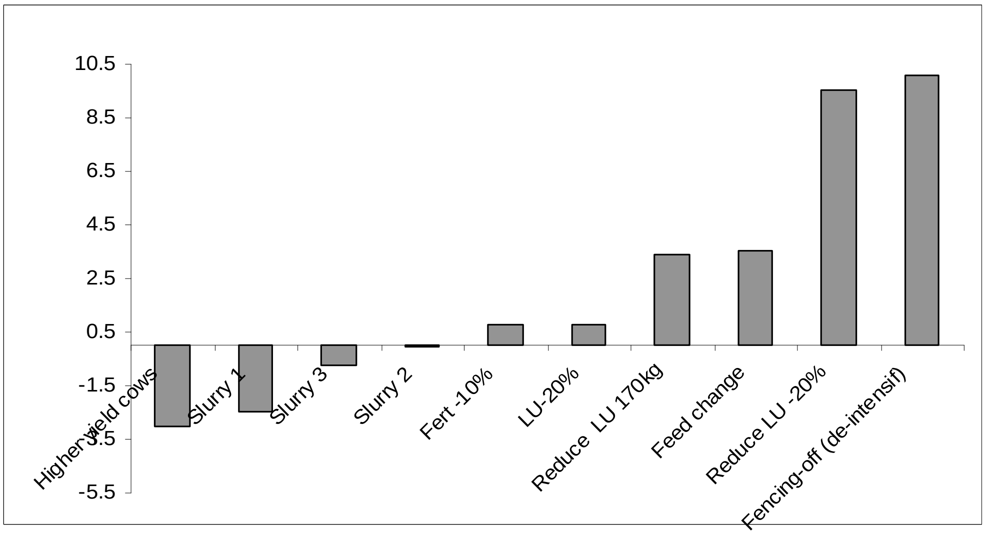
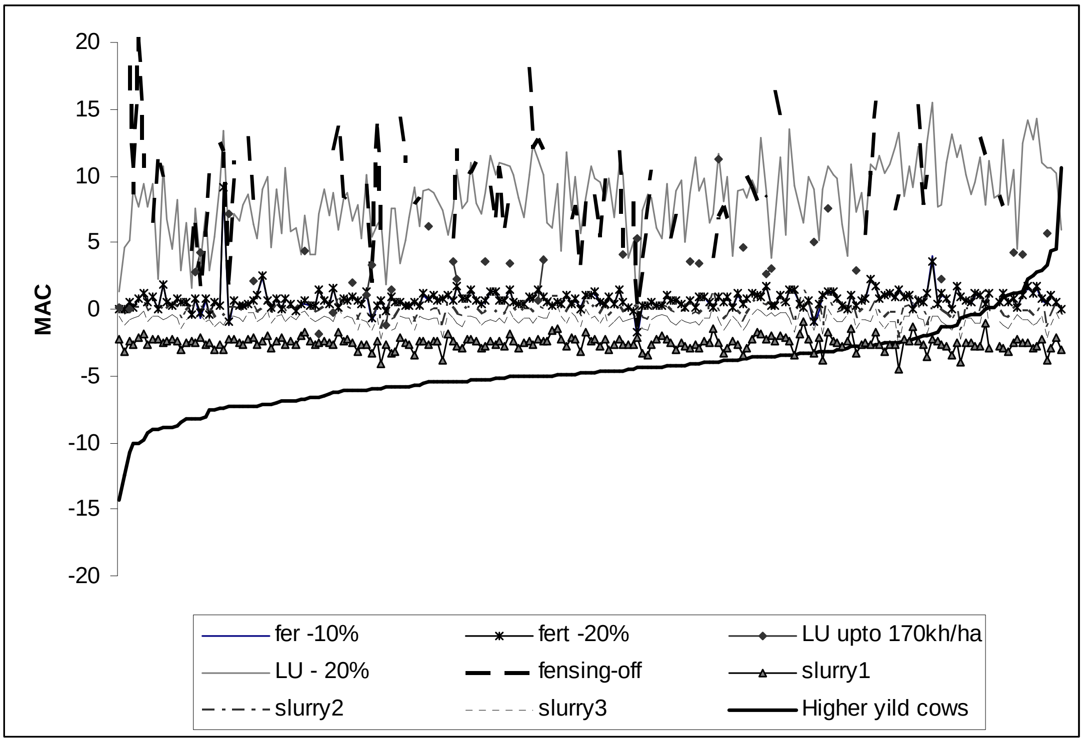


Figure I.4. MAC Curves for each mitigation strategy for all farms (€/kg N Ha^{-1})



In Figure 4 the farms are ranked by the most cost-effective aggregate MAC. If the ranking of mitigation strategies was the same for all the farms in the dataset, the lines would be parallel and would not cross. However, as can be seen in Figure 4, the lines cross a number of times indicating different magnitude and ranking of the MACs for individual farms. There is no strategy that is strictly dominant for all dairy farms in the sample. This has very important policy implications and suggests that any policy measure introduced in a rigid manner will not produce the economically most efficient result across individual farms.

I.7 Conclusion and Discussion

A wide range of policy options are available to agricultural decision-makers in designing rational economic responses to the continuous pressure to reduce N losses from farmed land. A wide range of research exists which describe different policy measures to reduce N losses to watercourses from agricultural land. The choice of practical mitigation strategies is tightly connected to the N cycle in the agricultural and biophysical environment.

Eight strategies for N reduction were considered in this paper: 1) inorganic fertilizer reduction by 10 %; 2) inorganic fertilizer reduction by 20 %; 3)LU reduction to achieve N

170kg ha^{-1}; 4) 20% LU reduction; 5) change in feed mix; 6) fencing off adjacent streams; 7) higher yield dairy cows; 8) efficient slurry application. All the mitigation strategies discussed here could potentially lead to reduction in N losses (keeping other factors constant) from agricultural land. In addition, in some instances a double-dividend may be achieved of a reduction in N application without affecting output. These strategies represent the most straightforward means of N reduction. However, this list is not exhaustive.

The MAC methodology used in this paper extends existing research in the area and offers an additional tool for decision-makers for efficient policy design. Results from this study indicate (on average) that farm GM per hectare declines under all strategies except in the higher yield dairy cows and slurry scenarios, which allow efficiency gain on the farms. These strategies led to an increase in GM per hectare of 5.9 % and 0.4%, 0.1%, 0.3% respectively. The smallest loss (0.2%) in the farm GM per hectare was produced by the fencing off scenario when intensification of production is considered. The largest decline in farm GM per hectare is observed under the 20 % reduction in livestock numbers scenario at 21 %. If farmers were to use more efficient feed in an effort to decrease N excreted by the dairy cattle, they would experience on average a 6.1 % decline in the dairy enterprise GM, which would be due to a 25 % increase in feed costs.

Increasing the breeding index of dairy cows achieves higher milk yields per animal and reduces the herd size. This would produce a 7.1 % increase in the enterprise GM due to the direct cost reduction of 11.8 % associated with the reduction in animal numbers. However, it has to be noted that due to data limitations a number of assumptions were made while modelling this strategy and careful consideration and further research is required before final conclusions can be drawn in this regard.

All the mitigation strategies produce a reduction in total N, however, some allow for higher total N reduction than others. Over 12 % of total N can be abated by cutting chemical N usage by 20 %. Relatively high total N reduction can be achieved by reducing fertilizer application by 10 % and decreasing the number of LU by 20 % - 6 % and 11.8 % respectively. Increasing the breeding index of dairy animals would allow farmers to abate 3.9 % of total N.

MAC analysis indicates that a number of the strategies (changing season/method/both of slurry application and increasing the breeding index) have negative signs which means that these mitigation strategies on average would not only result in a decrease in total N introduced into the environment but would reduce costs at farm level. The mitigation strategies with the largest average MAC were LU reduction by 20 % and fencing of watercourses, caused by the large abatement costs associated with these strategies as the higher the positive MAC the more expensive it is to abate each unit of total N for farmers.

The MAC curves for the mitigation strategies cross a number of times at individual farm level indicating that no strategy is strictly dominant for all farms across the sample. Individual farms have their own MAC ranking of the measures. The mitigation strategy that is the most cost-efficient at the aggregate level may not be the most cost-efficient at the micro farm level. Efficient policy should reflect this and allow flexibility and innovation at farm level to respond to any policy objective in this area. However, there may be increased transaction costs to establish the most efficient mitigation strategies at farm level.

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