USING A FARM MICRO-SIMULATION MODEL TO EVALUATE THE IMPACT OF THE NITROGEN REDUCTION MITIGATION STRATEGIES.

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Abstract: With the deadline identified by the Water Framework Directive (Directive 2000/60/EC) approaching in 2015, policymakers face increasing pressure to introduce new regulations to achieve water quality targets. Agriculture is one of the contributors of diffuse pollution entering watercourses and hence will come under pressure to further reduce pollutant loads. This paper describes a microsimulation model that allows the Cost per Unit Abated (CPUA) for eight farm-level measures that could potentially reduce nitrate loss from agricultural land on Irish dairy farms to be estimated. Results from this study indicate that almost all of the considered measures will lead to reductions in farm gross margins. However, some of these measures can be still implemented at preferable cost-effectiveness ratios. Furthermore we observe variation in the ranking of the measures by CPUA across farms suggesting that a "one-size-fits-all command-control" approach may place unnecessary costs on some farms where alternative policies may lead to N reduction at lower cost. We also conduct a sensitivity analysis of impact of input/output price changes on the CPUA ranking and show that the ranking of the CPUAs is sensitive to price and resultant quantity changes. Hence, focusing on the average CPUA nationally overlooks the heterogeneity of impacts across individual farms, potentially leading to suboptimal policies being implemented and highlights that policies should incorporate a degree of flexibility over time to reflect changing market realities.

Key words: river quality, WFD, microsimulation modelling, farm level models, policy impact

JEL Code: Q1, P28, P32

I.1 Introduction

Along with climate change and biodiversity loss, nitrogen (N) pollution is one of the most serious environmental challenges facing the planet (Giles, 2005). It has been estimated that nitrogen pollution from farms, vehicles, industry and waste treatment is costing the EU up to £280bn (320bn Euros) per year (Harrabin, 2001). In addition to problems in relation to drinking water quality, excessive N has been found to have a detrimental impact on biodiversity within the aquatic system. Some of the harmful environmental effects associated with N include problems with soil and water acidification, contamination of surface and groundwater resources, increased ozone depletion and greenhouse gas levels, and loss of biodiversity (Elser et al., 1990, Fraser and Chilvers, 1981, Sullivan et al., 1991, Yiridoe and Weersink, 1998).

In Ireland as in other EU countries, nitrate enrichment of watercourses is an important environmental issue. The Environmental Protection Agency Ireland (EPAI) in Ireland reports that in 2008 out of 180 nitrogen monitoring river sites, five sites had the highest values of N; 7 percent of groundwater monitoring sites failed to comply with the Irish Threshold Value concentration in the same year and 1 percent failed to comply with the Drinking Water maximum allowable concentrations, which is related to areas with more intensive agricultural practices (John, 2009). Additionally, the EPAI classifies 21 percent of river channels as being slightly polluted, 10 percent as being moderately polluted and 0.5 percent as being seriously polluted (John, 2009). The main impact of excess nutrients in water bodies is eutrophication, which causes an increase in biological and chemical oxygen demand and an unpleasant odour from the water, as well as a loss of habitats, changes to the river bed that in turn affect ship/boat navigation and negatively impact on recreational usage (Johnson et al., 2010, Novotny, 2003). Thus, there are significant socio-economic effects associated with nutrient enrichment in addition to the environmental effects.

At the same time, N is an important nutrient for the reproduction and growth of all organisms. Current levels of agricultural output could not be achieved and maintained without the widespread use of both synthetic and organic forms of N fertilizers (Merrington et al., 2003). Thus, alleviating pressure on water quality is likely to impose costs on the agricultural sector. However, in excess, N becomes a pollutant (Doole, 2012).

The complexity of environmental interactions poses a problem for researchers in identifying the sources of pollution and establishing robust causal relationship between different human activities and the volume of pollutants in streams. Lally et al. (2009) state that emissions of organic and inorganic nitrogen cannot be observed at a reasonable cost. O'Donoghue et al. (2014) studied the statistical relationship between water quality at over 3,000 monitoring sites in Ireland and human activities in the upstream areas and found that there was a significant statistical relationship between agricultural activities (in addition to other activities) and lower water quality in the downstream areas. This is in line with the findings of the DEHLG (2010), which states that intensively farmed agricultural land may be a source of excess nutrients in Irish waters.

A large volume of literature discusses the diffuse pollution from agricultural land. These studies identify a number of pollutants from agriculture that may present a potential problem to the wider environment and to water resources in particular, and the main pressure to water quality comes from nutrient enrichment (Donohue et al., 2006, Donohue et al., 2005, Merrington et al., 2003, O'Donoghue et al., 2014, Ritter and Shirmohammadi, 2000, Novotny, 2003, Lovelock et al., 2009, Doole, 2012, Doole et al., 2013, Schulte et al., 2006). The N pathways and its transformations in the environment are very complex and it can be difficult to establish a direct link between the potential sources and the affected areas. A number of studies have attempted to link human activities and impaired water quality. Donohue et al. (2006) and O'Donoghue et al. (2014) identify a number of factors including intensive agricultural activity and human settlement, as exhibiting a high correlation with downstream water quality in Ireland. This is in line with international research (see (Merrington et al., 2003, Novotny, 2003, Zhang et al., 2012)).

Increasing public awareness of and demand for environmental amenities is changing attitudes about agriculture and the agricultural industry's implicit property rights (Batie, 1988). To address these issues, a number of policy mechanisms have been introduced to improve water quality. At the EU level, the Water Framework Directive (WFD) (Directive 2000/60/EC) requires that (a) all waters are restored to at least "good" quality and that (b) water currently classified as "pristine" quality is maintained. Other EU legislation that aims to restrict pollution of water bodies and to protect their habitats (Habitat Directive (Council Directive 92/43/EEC), Freshwater Fish Directive (Council Directive 78/659/EEC), Birds Directive (Council Directive 79/409/EEC)), to protect the uses of the streams (Drinking Water

Directive (Council Directive 80/778/EEC), Bathing Water Directive (Council Directive 76/160/EEC), Sewage Sludge Directive (Council Directive 86/278/EEC), Urban Waste Water Treatment Directive (Council Directive 91/271/EEC)), to restrict nitrogen and other pollutants' loss to overland/ground waters (Nitrates Directive (Council Directive 91/676/EEC)) amongst others. Perhaps the most comprehensive legislative document to date is the WFD, which not only protects water resources from deterioration but also demands improvement in water quality to 'good ecological status' by 2015. One response to this change is a growing use of public policy options for mitigating agricultural pollution problems. Specifically farmers are encouraged and often required to adopt a range of practical farm management solutions such as livestock, manure and land management to reduce N pollution.

The Nitrates Directive (Council Directive 91/676/EEC) was introduced in 1991 to control N losses from agriculture. In Ireland the Good Agricultural Practice regulations (European Communities (Good Agricultural Practice for Protection of Waters) Regulations, 2010) were introduced to implement the Nitrates Directive. These regulations place restrictions on the period during which application of fertilizer is allowed; the amount of manure and inorganic fertilizer that is applied per hectare; the distance to a water body for fertilizer application; ploughing activities; and also impose requirements on the minimum storage capacities for livestock manure. 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 under 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 lead to significant progress towards meeting the WFD water quality objectives nationally, additional efforts may be required at a local level.

There is some evidence, that despite the efforts of Irish farmers to reduce N loss from their land, the production processes used and the prevailing weather conditions still lead to the loss of nutrients to the wider environment (Donohue et al., 2006, John, 2009). Recent evidence has shown that there have been improvements over time, possibly as a result of Agri-

Environmental measures and improved nutrient management on farms (O'Donoghue et al., 2014). However, more effort is still required to mitigate N pollution in Ireland.

Given the wide range of potential mitigation measures, a number of studies such as those by Cuttle et al. (2007) and DEFRA (2004), using representative farm types, have estimated the relative costs of various measures aimed at reducing diffuse water pollution from agriculture in the UK through linear programming measures. More recent work by (Fezzi et al., 2010, Fezzi et al., 2008) have analysed the effect of farm management measures aimed at reducing N losses across a wide variety of individual farm types. Their analysis reveals high variability in impacts across different farm types. Mitigation measures, thus, need to be targeted at the individual farm level since average national level analysis will not reflect the heterogeneity of impacts across individual farms.

This paper explores the costs associated with a range of potential N mitigation options in Irish context and provides decision-makers with an economic analysis to aid in the decision-making process concerning pollution mitigation policies for the agricultural sector. The cost-effectiveness of different farm level N mitigation strategies is investigated for each N unit reduction for each of the measures. This allows the lowest cost to be identified. A number of economic analyses of possible mitigation measures in this area have been conducted to date (Cuttle et al., 2007, Fezzi et al., 2010, Fezzi et al., 2008, Hennessy et al., 2005). However, the modelling methodology utilised in this paper differs from those previously used in similar studies. Cuttle et al. (2007) and Hennessy et al. (2005) used a linear programming approach for their estimations. Their estimations have also been based on a representative (average) farm. Fezzi et al. (2008) used a farm accounting approach to estimate the effect of nitrate reduction strategies on dairy farms in the UK. They extended the previous analysis to include the farms in the nationally representative sample. In this paper, the analysis conducted using Irish data and a microsimulation approach is applied to obtain the estimates for predicting changes. In line with previous research, the economic impact of the possible N mitigation strategies is estimated. This paper adds to previous research by extending the analysis to Irish farms and by simulating changes at an individual farm level and, thus, creating a framework for farmers to make farm management decisions as well as assessing the economic policy impacts at micro-level. The strategies are ranked according to their cost effectiveness as captured by the cost per unit of N abated (CPUA) and compared for all measures. The ranking of the CPUAs for individual farms are also examined in order to establish if this ranking is homogeneous for all farms in the sample. The model is validated by comparing the results with two mitigation measures that have previously been assessed by Hennessy et al. (2005) and Fezzi et al. (2008) 1) a stocking rate reduction to achieve a maximum organic N of 170 kg per hectare; 2) a 20 percent livestock units (LU) reduction. The model is then extended to include five more mitigation measures consisting of seven measures in total: 1) a reduction of fertiliser application by 20 percent; 2) a reduction of livestock units to achieve 170 kg of organic N per hectare; 3) a reduction of livestock units by 20 percent; 4) a change of feed mix to reduce cows' dietary N intake; 5) the fencing off of watercourses to introduce a buffer zone; 6) the introduction of higher performing dairy breeds to improve the genetic merit of dairy cows 7) more efficient slurry application. Finally, the sensitivity of the results to changes in prices and quantities is investigated.

This paper, thus, extends existing literature in a number of ways. First of all, it is an Irish individual farm-level study and as such this model allows assessing impacts of various measures for individual farms. Second, by considering the impact of price volatility on the estimated costs associated with various farm management strategies aimed at reducing N pollution this study informs policy-makers of the possible implications of varying market conditions on the outcomes at a farm level. This is likely to be a fundamental issue in assessing the costs of implementing directives such as the WFD, since price volatility may mean that in addition to a need for targeting of measures at individual farm types these same measures may need to vary through time in response to prevailing market conditions. The scenarios chosen for analysis are among the most popular suggestions for farm management practices aimed at reducing N losses from agriculture.

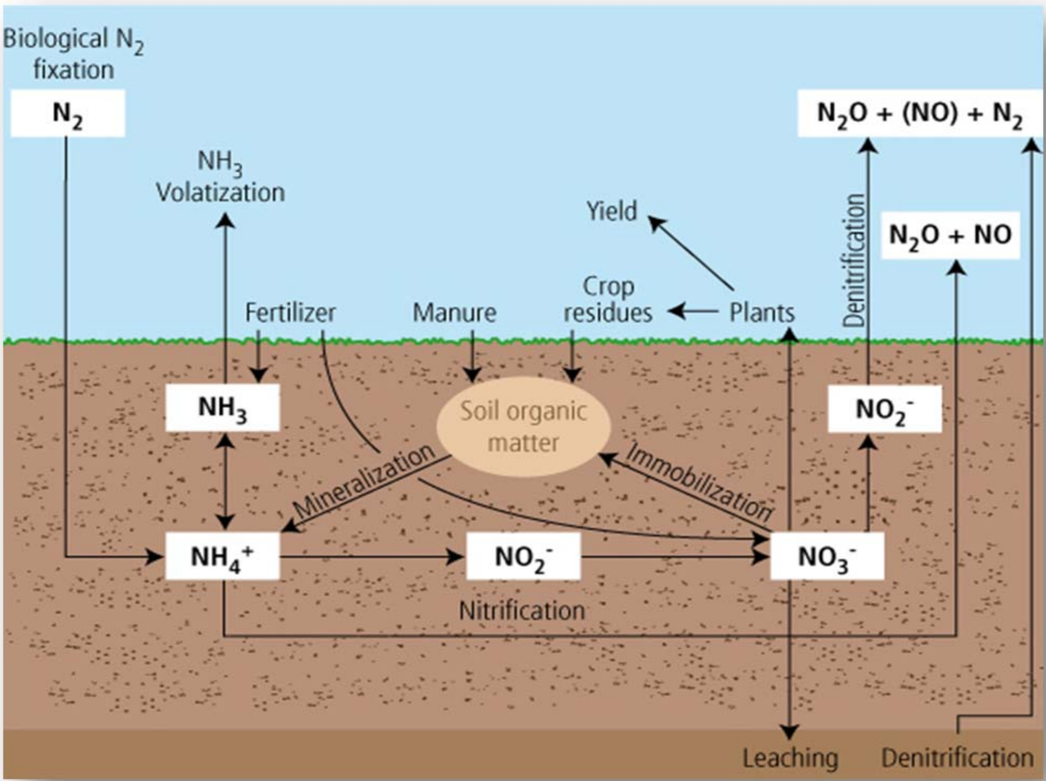
The rest of this paper is structured as follows: section I.2 gives a background of the study; in section I.3 farm management measures to reduce N pollution from agriculture are discussed; in section I.4 of this paper the methodology used is described; data sources are introduced in section I.5, the results are presented in section I.6 and discussion and the conclusion are given in section I.7.

I.2 Background

There is an extensive literature around mitigation strategies to reduce N losses from agriculture discussing a wide range of mitigation options (Byström, 1998, Novotny, 2003, Ritter and Shirmohammadi, 2000, Cuttle et al., 2007, Velthof et al., 2009). The primary factors that encourage N leaching from agriculture are over-fertilisation, excessive livestock numbers, improper use of manure, and exposure of bare soil during drainage periods (Bateman et al., 2007, Fezzi et al., 2008). Measures that aim to reduce N leaching should, thus, be targeted at these factors. The appropriate choice of mitigation strategies is connected to the N cycle in the agricultural environment. Combinations of these measures would aim to impact particular stages of the N cycle. 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. 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 et al., 2003). Figure I.1 illustrates an example of the N cycle (IFA, 2007).

Figure I.1. Nitrogen Cycle.



Source: (IFA)

Inputs of N into the environment 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 processes 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 de-nitrification, 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 (Merrington et al., 2003, National Research Council, 1993, Novotny, 2003, Ritter and Shirmohammadi, 2000). 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).

Fezzi et al. (2008) and Bateman et al. (2007) identify a number of key factors that encourage N losses including over-fertilisation, excessive livestock numbers, improper use 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 I.1 summarises the measures that are commonly proposed. Different issues and solutions are associated with each strategy.

As has been mentioned previously there are three main pathways through which different forms of N and its compounds circulate in the agricultural environment: inputs, transformations, and losses (Merrington et al., 2003). Mitigation strategies aim at controlling these pathways through either restricting excessive N input use or reducing N losses to the environment that are already in the system. Due to the weather and other environmental variations it is easier to target the reduction of N inputs to the ecological system as less N is introduced into the environment, less can potentially be lost through undesirable pathways (Merrington et al., 2003, Novotny, 2003, Ritter and Shirmohammadi, 2000). The input of N into agricultural system comes from chemical fertiliser application, animal manure and crop residue (IFA, 2007).

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 percentpercent 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 to access 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.

Some work has explored the costs of mitigation measures: Cuttle et al. (2007), Hennessy et al. (2005) and Lally et al. (2009) used linear programming in their estimations, while Fezzi et al. (2008) used a farm accounting approach to find the possible cost of the mitigation measures. This paper contributes to this nascent literature by introducing a model that allows the simulation of impacts associated with policy responses such as a change in N production, and resultant changes in farm income, at the farm level. The focus here is on seven measures related to a reduction in the N on farms, which are anticipated to lead to an associated reduction in N losses. To recap, these measures are: 1) a reduction of fertiliser application by 20 percent; 2) a reduction of livestock units to achieve 170 kg of N per hectare; 3) a reduction of livestock units by 20 percent; 4) a change of feed mix to reduce cows' dietary N intake; 5) the fencing off of watercourses to introduce a buffer zone; 6) the introduction of higher performing dairy breeds to improve the genetic merit of dairy cows 7) more efficient slurry application. These specific measures were selected for investigation as they are among the most common approaches recommended by environmental scientists and are also particularly suited to the structure of the Irish agricultural sector.

However, identifying the pressure points and the policy alternatives does not provide sufficient information for efficient decision-making. The information on the cost of the mitigation alternatives is needed to achieve environmental objectives in the most efficient manner. In addition, agriculture is a heavily subsidised sector in the EU, it generates narrow profit margins for many farmers so careful analysis is needed to assess the impact of alternative policy measures on farm incomes before any of them are transited into legislation.

The costs associated with the various options for reducing N losses can vary considerably and hence the use of cost-effectiveness analysis (as expressed in cost per unit abated - CPUA) is becoming increasingly popular as a means to choose between them (Domínguez et al., 2009, Blok et al., 2001a, Moran et al., 2008). Where a number of mitigation options exist, CPUAs of a number of alternatives in terms of their cost effectiveness and their ranking provide policymakers and other decision-makers with guidance as to the least cost policy option from a range of alternatives.

One issue that is frequently overlooked in CPUA analysis is the sensitivity of the results to changes in prices. According to the latest OECD/FAO medium term outlook projections, the prices of crops and of most livestock products will be higher in both real and nominal terms during the decade to 2019 than they were in the decade preceding the 2007/08 price spikes. Also, in the period since 2006 the agricultural sector has witnessed significant price volatility (Fao et al., 2011). To date, most of the concerns about price volatility are related to the potential negative effects on consumer welfare especially in poorer households from rising food prices. Instead, here the effect of price volatility on CPUA results is explored. In particular, the study conducted in this paper highlights that the assessment and in turn the ranking of mitigation measures will depend on the commodity and input prices prevailing in the particular period.

The differences in CPUAs and their ranking come from recently observed increase in price volatility. A number of factors contribute to this increased price volatility on agricultural markets. Firstly, the demand for food and feed crops for the production of biofuels increased dramatically. For instance, during the period 2007-2009 bio-fuels accounted for a significant share of global use of several crops – 20 percent for sugar cane, 9 percent for vegetable oil and coarse grains and 4 percent for sugar beet. It is generally expected that bio-fuel production will continue to exert considerable upward pressure on prices in the future. Secondly, agricultural commodity prices are becoming increasingly connected to oil prices through its effect on the price of fuel and fertiliser. Climatic factors have also placed a considerable upward pressure on agricultural prices in recent times. For instance, weather related low yields in important food exporting nations such as Australia, Canada, Russia and the US have brought strong market reactions and soaring prices. Finally increased affluence in developing countries and population growth are likely to increase demand for, and hence prices of, agricultural foodstuffs in the future (Fao et al., 2011).

I.3 Farm management measures to reduce N pollution from agriculture

As a result of legislative requirements to reduce N losses into the environment, the effect of a range of agricultural and agronomic practices generally referred to as mitigation measures, have been investigated (see Stark and Richards (2008) for a useful review). Some of the plethora of farm management practices that have been found to reduce N pollution include: land use change (Lord and Anthony, 2000, Saggar et al., 2007), reducing stocking rates (Di and Cameron, 2002, Oenema et al., 1998), changes in the timing and form of manure application (Chambers et al., 2000), use of cover crops (Hansen et al., 2007, Hooker et al., 2008) and manipulation of animal diets (van Groenigen et al., 2008, Velthof et al., 1998, de Klein and Monaghan, 2011). Perhaps the most straightforward approach to reduce N emissions is the adoption of less intensive grassland systems, through for instance, lowering stocking rates (Cuttle et al., 2004, Oenema et al., 1998). Although requiring a greater land area to achieve the same agricultural output, this would result in less nitrate leaching per unit of production than intensively managed grasslands. Changing agricultural and land use practices from high to low emission systems by, for example, converting from arable to extensive grassland farming (Lord and Anthony, 2000) or by converting from conventional to organic dairy farming has also been shown to substantially reduce N loss from agriculture.

Within livestock enterprises, N loss can be mitigated by changes in manure storage and manure application strategies (Chambers et al., 2000, Lalor et al., 2011). Livestock dietary manipulation has also been shown to improve N use efficiency by animals, reducing N excretion and hence its entry to the wider environment (van Groenigen et al., 2008, Luo et al., 2008). Reducing the duration of grazing per day and/or season can also significantly reduce the quantity of N excreted and deposited directly to the land (Luo et al., 2008). Finally the use of cover crops has been shown to be very effective in terms of reducing N losses (Hansen et al., 2007, Hooker et al., 2008).

When the use of chemical fertilisers exceeds the level required by crops, the excess is lost through groundwater, surface streams and/or via overland runoff. Reducing the use of chemical fertiliser is the most straight forward way to reduce nutrient inputs which in turn can lead to a proportional reduction of N introduced and subsequently lost to the environment.

The surplus N in the livestock diet is excreted (DEFRA, 2007). Reduction of the N content of the feed without the loss of the output or compromising on animal health is viewed as an attractive N mitigation option. Wright and Mutsvangwa (2003) report that switching from one feed to another can potentially reduce protein fed by 15-20 percent yearly and will reduce N excreted by the animals proportionally.

Livestock, particularly dairy cows, 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 and is known to be one of the polluting activities. A dairy cow produces 5.3 m^3 of slurry in 16 weeks of housing (European Communities (Good Agricultural Practice for Protection of Waters) Regulations, 2010), which contains approximately 19 kg of N. This manure/slurry has to be spread overland or exported from the farm. Livestock also deposits manure/urea directly on fields during grazing periods. In Ireland the Good Agricultural Practice regulations (European Communities (Good Agricultural Practice for Protection of Waters) Regulations, 2010) place a restriction on the amount of manure and inorganic fertilizer that may be applied per hectare - presently the amount is capped at 170 kg of organic N per hectare, with a possibility to derogate to 250 kg of N per hectare. It has been suggested in the literature that in order to achieve the objectives of WFD, the introduction of changes such as a 50 percent reduction in the application of fertilisers to crops and grass, sheep stocking rates to be halved and a reduction in cattle stocking rates of 20-25 percent may be needed (Bateman et al., 2006, Haygarth et al., 2003).

Excluding animals from the areas next to the streams (fencing) can substantially reduce the deposition of faecal material, turbidity from in-stream trampling and denudation of the stream banks (Novotny, 2003). If the areas adjacent to the streams are excluded from agricultural production completely then the environmental gains are greater still due to decreased fertiliser usage.

Another 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 the 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.

In Ireland over 95 percent of the national dairy herd is Holstein-Fresian breed. 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. There are a number of factors affecting milk output per cow including: breeding index, parity, season of calving, management factors (such as the choice of feed, milking intervals, milking frequency) and geographic location (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 on the farm. Economic breeding index (also known as EBI) of a dairy cow was developed by Teagasc and represents a monetary figure that is calculated on the basis of a number of dairy animal traits (for full discussion, see ICBF (2014)). However, in this paper by referring to breeding index, an unobserved index within the dairy breed that allows the herd to perform better in terms of milk output per animal is meant. Arguably, in short term, a farmer is concerned with the amount of milk per animal produced on their farm.

I.4 Methodology

Estimation of N produced on the farm.

The aim of the analysis undertaken in this paper is to develop a framework in which one can readily assess the impact of N reduction measures on farm N budget and on farm income within the context of implementation of the WFD. In doing so it is first necessary to decide how to estimate the farm's N budget. Often researchers focus on modelling the run-off and undesirable losses of N from farm land. This approach leads to difficulties for modellers as it requires the development of a separate hydro-geological model that would allow the prediction of N losses through different pathways to be made. This in turn requires a lot of hydro-geo-ecological data in very high resolution. Such data seldom exists nationally. As an alternative approach, the model discussed in this paper allows one to approximate N losses using a 'reduce inputs' approach. The assumption behind this approach is that if less N is introduced into the environment during the production process on the farm, then less is subsequently lost through undesirable pathways – via volatilisation, run-off, and /or leaching. A proportional reduction is assumed throughout.

The total N on a farm depends on the number of livestock units[1] (organic N) and on the amount of chemical fertiliser used as a part of the production process (chemical N). Haygarth et al. (1998) and Merrington et al. (2003) report that 70-80 percent of N ingested by the animals during grazing and/or feeding on concentrates is subsequently excreted in manure. The level of organic N for an enterprise *j* is calculated by multiplying the number of LU of type *k* in that enterprise of the farm (NLU_{kj}) by the annual N excretion rate of that LU type (E_k) and summing across the *K* types of LU. This is then added to the inorganic N for enterprise *j* and summed over the *J* enterprises to obtain the total N on the farm, as is given by:

$$N_i = \sum_j^J (\sum_k^K \left(E_k NLU_{kj}\right) + Inorganic\ N_j) \tag{I.1}$$

The 'annual nutrient excretion rates (E_k) for livestock' tables is used as published in Good Agricultural Practice for Protection of Waters (European Communities (Good Agricultural

[1] In Teagasc National Farm Survey (NFS) a dairy cow is taken as the basic grazing livestock unit. All other grazing stock is given equivalents as follows: Dairy cows 1.0; Suckling cows 0.9; Heifers-in-calf 0.7; Calves under 6 mths. 0.2; Calves 6-12 months 0.4 Cattle 1-2 years 0.7 Cattle over 2 years 1.0 Stock bulls 1.0; Ewes and rams 0.20 (lowland) 0.14 (hill); Lambs to weaning 0.00 (lowland), 0.00 (hill); Lambs after weaning 0.12 (lowland), 0.10 (hill); Hoggets and wethers 0.15 (lowland), 0.10 (hill). For more details see Connolly et al. (2008).

Practice for Protection of Waters) Regulations, 2010) to determine the N produced by each animal on the farm – 85 kg of N per dairy LU, 65 kg of N per beef LU and 7 kg of N per sheep LU[2]. The number of kilograms of chemical fertiliser purchased by the farmers was used to determine the amount of chemical fertiliser used on the farms.

Estimation of the farm profit.

Farm profit π_i is calculated as the farm's gross output (Y_i) less farm's direct costs (C_i) and fixed costs (FC_i). The level of farm gross output and direct costs determine a farm's profit (equation I.2):

$$\pi_i = Y_i - C_i - FC_i \tag{I.2}$$

Animal numbers and chemical fertiliser each affect the gross output volume (Y) and the direct costs (C) on the farms (equations I.3 and I.4). Farms in Ireland usually engage in more than one enterprise. Each enterprise is modelled separately here due to the fact that only dairy farms are considered. However, when the farm system is not important adopting a 'whole farm' approach may yield better estimates. X_{ij} is a vector of explanatory variables, where i denotes individual farm and j denotes each farm enterprise (dairy, beef or sheep), and variables include the size of farm, the volume of fertiliser and concentrate used, number of livestock units, forage area, etc. (see Table I.6 for a full list of variables used in the model for each function estimation). These variables determine the level of Y_{ij} and C_{ij} in equations I.3 and I.4. When more LU are on the farm, more output is produced, however more organic N is also produced on the farm and costs incurred by a farmer to feed and maintain animals are also greater.

$$Y_{ij} = (X_{ij} \mid \beta_j, \varepsilon_{ij}^{y}) \tag{I.2}$$

$$C_{ij} = (X_{ij} \mid \gamma_j, \varepsilon_{ij}^{c}) \tag{I.3}$$

Thus, through manipulating (reducing) the number of animals and the amount of chemical fertiliser used, farmers could reduce the N budget on the farm and hence reduce

[2] An N excretion rate of 7kg per sheep livestock unit is used in this paper, despite the fact that for lowland sheep the N excretion rate is 13kg (S.I. 378 of 2006). However, this excretion rate covers both the ewe and its lambs and would thus result in an over-estimate of N/ha on the farms and hence subsequently produce a lower cost per unit of N abated in the second scenario.

environmental pressures. A positive relationship is assumed between animal numbers, the amount of fertiliser and the value of gross output and costs.

Econometric techniques are utilised for determining the gross output and direct cost functions. Three production and three cost functions are estimated in this model: dairy gross output, dairy direct costs, cattle gross output, cattle direct costs, sheep gross output, and sheep direct costs (equations I.2 and I.3).

Approaches to production analysis

There are number of approaches that can be utilised in production modelling. They include general equilibrium models, econometric analysis and engineered functions (Arfini, 2012). The purpose of econometric analysis is to establish the effect that changes in inputs have on output and costs. Econometric analysis can take two directions: 1) micro-level production analysis based on individual units (e.g., farms); 2) macro-level analysis in which agricultural output is an input to production on the macro level (Bonaccorsi and Daraio, 2005). In this paper only the former is discussed. The main approaches used in a micro-level production analysis are the production function approach (O'Donoghue and Lennon, forthcoming) and the production frontier analysis in form of stochastic production frontier (Bonaccorsi and Daraio, 2005, Mawa et al., 2014)). In the first instance, the estimations seek to establish an average relationship between inputs and outputs/costs by specifying a functional relationship that explains the observed data (Bonaccorsi and Daraio, 2005). This exercise is carried out using either parametric (when an underlying data functional forms specified), nonparametric (without referenced to a specific functional form), or semi-parametric approaches (when part of the model is parameterised and another part is not) (Bonaccorsi and Daraio, 2005).

Stochastic production analysis are normally used in productivity analysis when, the frontier that envelopes that data points is estimated instead. In this data analysis all data points on the frontier are considered to be “efficient” and the distance between the rest of the data points and the frontier is measured through estimation of a farm-specific efficiency scores and the factors explaining efficiency differentials (Kumbhakar and Lovell, 2003, Green and O'Donoghue, 2013, Coelli et al., 2005); (Cooper et al., 2013, Mawa et al., 2014).

In this paper the production function approach is used throughout since production efficiency is not the focus of this research. Separate gross output and direct cost functions are estimated, despite the fact the duality approach - first introduced by Shepard in 1953 - allows one to estimate a cost function based on a profit or revenue since they are all a special case of a restricted profit function (Fuss and McFadden, 1978).

The duality theory states that any production function has an underlying cost function or correspondence. Assuming fixed prices the farmers are assumed seeking to determine the combination of inputs that allow profit maximisation. If a farm's output is $y=f(x)$, its revenue is $h(x)$ and this farm is facing costs $c=g(x)$, then profit is maximised where $h'(x)-g'(x)=0$, where $h'(x)$ is a marginal revenue, $g'(x)$ is marginal cost and x is units of inputs. Thus, production, revenue or cost function need to be known to build a model (Debertin, 2012). The Duality Theory helps in this case as it states that only one of these functions needs to be known as a cost function is an inverse to production function and (providing prices are fixed) can be derived from it. For a production function $y=f(x)$, the cost is $x=f^{1}(y)$ – an inverse function (Debertin, 2012).

A plethora of literature has discussed the duality between production, profit and/or cost functions, which implies that the estimates from one function can theoretically be transferred to the other, and, thus, there is no need to estimate both production and cost functions (Quiggin, 2002, Chambers et al., 2000, Chambers and Quiggin, 1998, Lusk et al., 2002, Debertin, 2012).

The dual approach proves to be a useful tool in many analyses. However, it is not pursued in this paper for the following reasons. The dual approach is normally used in optimisation models with a view to determine the optimal combination of inputs and outputs for profit maximization/cost minimisation. The model developed here is not a maximization/minimization problem as the purpose is not to explore conditions under which farmers would optimise their production, but rather to simulate the changes in "what if" scenarios based on the observed data. The focus is on the predictive ability of the model rather than on the coefficients per se and models based on estimation of simple relationships have been found to perform well in this regard (e.g. Fezzi et al. (2010), O'Donoghue and Lennon (forthcoming)). O'Donoghue and Lennon (forthcoming) used this approach in their farm income generation model in which they estimated farm level production and cost functions and validated their results by simulating data and comparing simulated results with the actual data. The difference between their model and the model reported here is that while they used a "whole farm" approach, here the impacts are assessed at an enterprise level.

Moreover, Thompson and Langworthy (1989) showed that identical primal and dual results cannot be achieved due to risk, stochastic error and/or the functional form chosen. Lusk et al. (2002) investigated the conditions under which the production, profit and cost functions estimates yield the same results and discovered that it is possible only under perfect conditions when the functional form exactly matches the data and there is no measurement error in the data. Their findings suggest that a measurement error as small as 0.01 percent can lead to considerable differences between dual and primal estimates (Lusk et al., 2002). Due to the fact that enterprise data on the farm is not perfect and often farmers allocate expenses like labour costs to different enterprises based on approximation rather than actual data, estimating cost from production estimates yield the results that will be way off the primal estimates.

Another reason for not using the dual approach here is that when functions that have a large number of inputs are used, deriving the inverse function may be practically impossible exercise. For example, for two input Cobb-Douglas production function:

$y=Ax_1^{\beta1}x_2^{\beta2}$

the dual (and the least cost) cost function is:

$c=y^{(1/(\beta1+\beta2))}A^{(-1/(\beta1+\beta2))}(\beta_1^{-1}\beta_2 v_1+v_1)^{(\beta1/(\beta1+\beta2))}(\beta_2^{-1}\beta_1 v_2+v_2)^{(\beta2/(\beta1+\beta2))}$

(Debertin, 2012). Furthermore, in this research, in the estimated functions, both value and volume variables are utilised to accommodate the simulation procedure and since deriving a dual cost function is based on relative price elasticity, a dual approach is not suitable in this framework.

Functional Form

Choosing a functional form for parametric econometric analysis is another important task. There are a variety of functional forms one could use when estimating output or costs and since the true functional form cannot be known, the problem is to choose the form that best suits the task at hand (Griffin et al., 1987).

The most commonly used functional forms in production analysis are the Cobb-Douglas and trans-log (which is generalised form of a Cobb-Douglas function), although other functional forms are sometimes used (Lusk et al., 2002, Flichman, 2011, Mawa et al., 2014)). Lusk et al.

(2002) state that from a theoretical point of view there is no advantage in using one functional form over another for estimating the true but unknown function underlying data.

Both translog and Cobb-Douglas functional forms have been used extensively in production analysis (a few examples include (Švarc and Švarc, 1989, O Neill and Matthews, 2001, Liu, 2002, Mawa et al., 2014)). Liu (2002) conducted a comparative analysis of the output studies for libraries and out of nine studies examined seven used Cobb-Douglas functional forms and two translog. There are advantages and disadvantages in using both of these functional forms, they are both linear in parameters and, thus, can be estimated using least squares method (Griffin et al., 1987, Mawa et al., 2014).

Translog is a flexible functional form, however it is hard to estimate, and difficult to interpret, it requires estimation of a large number of parameters *(k+3+k(k+1)/2)*, where *k* is a number if inputs, which with a small sample data can lead to a big loss of degrees of freedom[i] (Mawa et al., 2014). Cobb-Douglas, on the other hand, is an easy to estimate and interpret function, it requires estimation of a much fewer parameters *(k+3)* than translog function and, thus, is very useful in production analysis.

Romer (2011) states that Cobb-Douglas function is "a good approximation to actual production functions". In this paper, production and cost functions are estimated using ordinary least squares (OLS) regressions. A similar parametric approach was used by Fezzi et al. (2010) who used a linear regression approach (assuming constant returns to scale) to estimate the change in farm gross margin that arises from different policy measures and by O'Donoghue and Lennon (forthcoming) who used Cobb-Douglas functional forms for regression analysis in their Farm Income Generation model. In contrast to Fezzi et al. (2010), who estimated a single function – a change in farm gross margin resulting from policy change, here separate equations for gross output and direct costs are estimated and then a gross margin is calculated. O'Donoghue and Lennon (forthcoming) have also estimated their output and cost functions separately.

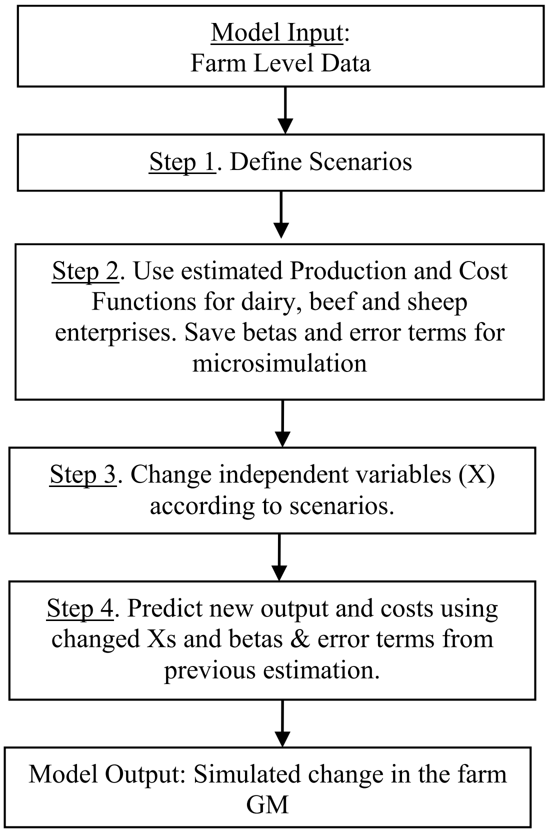
Estimating functions separately allows the impact of shocks on these components to be explored and the simulation of changes in these components at a farm system level and, thus, maybe more useful for modelling purposes. Another reason for using the same functional forms and variables as O'Donoghue and Lennon (forthcoming) is that their model is based on

Irish farm data. They have also tested, calibrated and validated their model, thus, making it a ready to use tool for farm data analysis.

Developing a micro-simulation model

The model (as described in equations I.1- I.4) allows the simulation of changes in farm profits due to gross output or direct costs changes at an enterprise level. The impact of different measures to reduce N can differ in both the economic and in the environmental dimensions across farms, thus, the analysis should be carried out at a farm level. Microsimulation techniques allow a modeller to conduct analyses at this scale. Microsimulation has been used for many years and is an effective tool for evaluating the socio-economic impacts of different mitigation options where it is difficult or impossible to conduct a real life experiment (Merz, 1993, O'Donoghue et al., 2012). It has been widely used for income generation modelling, tax system evaluation and pension schemes evaluation inter alia (Mitton et al., 2000, O'Donoghue et al., 2012). Microsimulation can be carried out using various techniques, for example, linear programming (Hennessy et al., 2005), partial budgeting (Fezzi et al., 2008) or econometric regression analysis (Fezzi et al., 2010, O'Donoghue and Lennon, forthcoming).

Figure I.2. Simulation Model Flow Diagram



All of these techniques allow one to model changes at the farm level. The choice of a particular technique depends on the objective of the model. Hennessy et al. (2005) utilise the FAPRI-Ireland Farm Level Model, which is a dynamic gross margin maximizing model and was first described by Breen and Hennessy (2003). The linear programming approach allows model optimization, however, in the model developed in this paper the aim is not to optimize farm production but rather to understand how the farm system affects the costs of the mitigation measures. In the Fezzi et al. (2008) farm budget model the underlying assumption in the 20 percent LU reduction scenario is that the output and costs would be reduced by 20 percent as well. However, this assumption may not hold in reality as the relationships and dependencies between variables are more complex. In this paper Fezzi et al. (2010) approach is followed in adopting a regression framework. Regression analysis was chosen for this model as the most appropriate technique for estimations as it allows one to capture the marginal effect of changes in the variables of interest, e.g. the change in the number of livestock units. The schematic of the overall simulation procedure is depicted in Figure I.2.

In order to validate the model as a case study two mitigation options that have previously been estimated by Hennessy et al. (2005) and Fezzi et al. (2010) are explored: 1) a stocking rate reduction to achieve maximum organic N of 170 kg per hectare; 2) a 20 percent LU reduction. These measures would lead to changes in the farm inputs and/or outputs through reductions in the dry stock, fertiliser usage, feed change etc. The model input is the farm level data which is described in the next section of this paper.

The impact of the alternative mitigation measures on individual farm profit (π_i) is simulated using estimates of gross output and direct cost functions based on farm-level data (equations I.2 and I.3).The fixed costs are not affected by the scenarios in the simulations, thus, the changes in the farm profit are due to changes in farm gross margin (GM) (equation I.5).

$$GM_i = Y_i - C_i \tag{I.5}$$

$$Y_{ij}^{\circ} = (X_{ij}^{\circ} \mid \beta_j, \varepsilon_{ij}^{y}) \tag{I.6}$$

$$C_{ij}^{\circ} = (X_{ij}^{\circ} \mid \gamma_j, \varepsilon_{ij}^{c}) \tag{I.7}$$

$$\pi^{\circ}_{ij} = \sum Y^{\circ}_{ij} - \sum C^{\circ}_{ij} \tag{I.8}$$

$$\Delta\pi_i = \pi^{\circ}_i - \pi_i \tag{I.9}$$

The simulations are carried out by holding the regression coefficients (β_j, γ_j) and the error terms (ε^{y}_{ij}, ε^{c}_{ij}) constant and changing the explanatory variables (X°_{ij}) according to the scenarios (in the case study scenarios here it is the number of LU that is altered). When the parameters of the model are estimated the new levels of gross output and direct cost are predicted for each enterprise (denoted as C°_{ij}, Y°_{ij} in equations I.6 and I.7). The results are then aggregated to the farm level (equation I.8). The impact of the simulated changes in the animal numbers and/or fertiliser is the difference between farm profit before (π) and after the change (π°) (equation I.9).

$$N_i^{\circ} = \sum_{j}^{J} \left(\sum_{k}^{K} \left(E_k NLU_{kj}^{\circ} \right) + Inorganic\ N_j \right) \tag{I.10}$$

The changes in N come from the change in animal numbers according to the particular scenario. The adjusted number of livestock units is NLU°_{ij} (equation I.10), where k is a type of a LU – dairy, beef or sheep.

$$NLU^{\circ}_{ki} = (0.8 \times NLU_{ki}) \tag{I.11}$$

In the second scenario the number of LU on each farm is reduced by 20 percent for each enterprise (equation I.11) and the new N° on the farm is calculated as in equation I.10.

The final change in N on the farm is the difference between the N level before the simulations and the level, N°, which is simulated for the farm after the mitigation measure introduction (equation I.12).

$$\Delta N_i = N^{\circ}_i - N_i \tag{I.12}$$

$$CPUA = \Delta\pi_i / \Delta N_i \tag{I.13}$$

Thus, this methodology allows one both to simulate the changes in farm profit and to simulate the change in N on the farm as a result of the mitigation measures. It can potentially be used by decision-makers in determining not only the level of abatement that can be achieved through different measures and the cost associated with them but also to compare the cost efficiency (expressed as *CPUA*) for each individual farm (equation I.13).

Model Extensions

After the validation, the model is extended to include five more scenarios, thus, seven scenarios were simulated in the model altogether: 1) the reduction of inorganic fertiliser by 20 percent; 2) the reduction of Livestock Units to achieve 170 kg of N per hectare; 3) the reduction of LU by 20 percent; 4) a change in the feed mix; 5) the fencing off of adjacent streams (and subsequent de-intensification of production); 6) a change in the method and the time of slurry application; 7) an improvement in the breeding index of the dairy herd. In each of the simulated scenarios the level of N is adjusted in line with the assumptions of the scenario. The new level of N° is calculated for each scenario as shown in Table I.2.

Table I.2. Implication of each policy scenarios for Nitrogen levels.

Scenario	Level of Nitrogen in Scenario
1) the reduction of inorganic fertiliser by 20 percent;	Inorganic Nj˚= 0.8 x Inorganic Nj $N_i^\circ = \sum_j^J (\sum_k^K (E_k NLU_{kj}) + Inorganic\ N_j^\circ)$
2) the reduction of LU to achieve 170 kg of organic N per hectare;	Farms are assumed to reduce LU starting with the enterprise that has the lowest gross margin per LU to reach 170 kg of N per hectare. The adjusted number of livestock units is : $N_i^\circ = \sum_j^J (\sum_k^K (E_k NLU_{kj}^\circ) + Inorganic\ N_j)$
3) the reduction of LU by 20 percent;	$N_i^\circ = \sum_j^J (\sum_k^K (E_k NLU_{kj}^\circ) + Inorganic\ N_j)$
4) a change in the feed mix;	A reduction by 15percent in the amount of N excreted by dairy cows is assumed; the excretion rate for other LU is unchanged. The adjusted excretion rate is E˚ $N_i^\circ = \sum_j^J (\sum_k^K (E_k^\circ\ NLU_{kj}) + Inorganic\ N_j)$
5) the fencing off of adjacent streams (and subsequent de-intensification of production)	$N_i^\circ = (\sum_j^J (\sum_k^K (E_k NLU_{kj}^\circ) + Inorganic\ N_j)) x \frac{NewFarmSize}{OriginalFarmSize}$
6) a change in the method of slurry application from splash-plate to trailing shoe;	$N_i^\circ = \sum_j^J (\sum_k^K (E_k NLU_{kj}) + Inorganic\ N_j^\circ)$
7) an improvement in the breeding of the dairy herd.	Farms are assumed to reduce the number of dairy cows to maintain GO at its pre-existing level. Other livestock units remain unchanged. The adjusted number of livestock units is : $N_i^\circ = \sum_j^J (\sum_k^K (E_k NLU_{kj}^\circ) + Inorganic\ N_j)$

The CPUA for a scenario is then calculated as explained in equation I.13 and the results for each measure on average and for each individual farm are compared. The estimation of farm-level CPUA requires knowledge of the effects of the proposed mitigation strategies on the gross output and direct cost functions of each farm as well as the amount of nutrient loss mitigated as a result of each strategy. The ranking of the mitigation strategies from the cheapest to the most expensive per unit of N potentially mitigated allows one to compare the costs of the measures.

Assumptions behind the Mitigation Strategies

In order to formalise the model, certain assumptions had to be made within each measure. In the fertilizer reduction scenario the volume of chemical fertilizer used on dairy farm is reduced by 20 percent relative to the current level used on the farms. In Scenario 2, the farmers are assumed to drop the livestock with the lowest gross margin per LU. In Scenario 3, it is assumed that each type of livestock is reduced by 20 percent.

In Scenario 4, it is assumed that farmers make alterations to their feed mix to ensure a reduction by 15 percent in the amount of N excreted by dairy cows in line with the findings of Wright and Mutsvangwa (2003). Wright 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), Fezzi et al. (2008) - that there is an extra cost associated with this strategy. In the model described in this paper a 25 percent increase in the cost of the new feed mix is assumed. This cost is associated with the higher price of the new feed and of protein monitoring.

In Scenario 5, it is assumed that adjacent streams are fenced off. The costs associated with this measure include the cost of fence construction and maintenance as well as a loss of grazing/production land. The cost of the fencing includes the actual cost of erecting the fence of €0.90 per metre and the cost associated with the reduction in productive land area. Ten meter zones are assumed to be fenced off. Two possible sub-scenarios are estimated: 1) 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; and 2) the possible intensification of production where farmers would keep the existing livestock numbers despite the reduction in overall 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 cessation of fertilizer use on the land taken out of production. In the case of intensification (increase in a farm's stocking rate) 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 objectives as there will be an increase in both organic and chemical N per hectare. Increases in organic N per unit area will result from an increase in stocking rates due to a decrease in land available for spreading slurry. Increases in chemical N may result if more chemical fertilizer is used.

In Scenario 6, the effect of changes in the application of manure from the splash plate (SP) (spraying manure over the field) method to the trailing shoe (TS) method (depositing manure directly on the top layer of the soil) are examined. The TS method allows more precise manure/slurry application reducing losses of N through volatilization in the form of greenhouse gases so that less chemical fertiliser is required. The SP method of application allows 12 percent of N in manure to be available for plant uptake while the TS method allows 22 percent and, thus, decreases the amount of chemical fertiliser required to support sufficient grass cover (Lalor et al., 2011). Two 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. Farms are assumed to initially all use the splash plate and then shift to the trailing shoe method in scenario 6. The actual level of N reduction will differ depending on the stocking rate of the individual farms. Switching from summer to spring application has no extra cost. There is an extra cost of €0.77 per m^3 of slurry (Lalor et al., 2011) 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, the 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. It is reported that 34 percent of slurry is spread by farmers during spring and about 50 percent during the summer and the remainder (16 percent) is spread in autumn using mainly the SP method of application (Hyde et al., 2006). The availability of slurry N in summer and autumn is similar; hence it is assumed here that 66 percent 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 I.3). The TS method of application increases N availability in slurry by 10 percentage points both in summer and in spring (Lalor et al., 2011).

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 (percent)	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			

A dairy cow produces 5.3 m^3 of slurry in 16 weeks of housing (European Communities, 2010), which contains approximately 19 kg of N. In a summer application only 12 per cent of this is available for crop/grass uptake, and in a spring application 21 percent is available. The demand for chemical N fertilizer depends on the farm stocking rate, e.g. if a stocking rate on a farm is 2 LU per hectare, 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 percent of slurry is spread during the summer and 34 percent in spring (at the aforementioned stocking rate) 97.63 kg per cow of chemical N fertilizer is required instead of 100.5 kg.

In Scenario 7 the effects of increasing the breeding index is examined. This can potentially allow achieving higher levels of performance from each animal in a herd, which in turn reduces the amount of N lost per unit of output (Walsh et al., 2008). It is assumed that farms maintain gross output at its current level and reduce their LU accordingly after moving to more productive breeds and by so doing, reduce the amount of N lost per unit of output. Data on breeding indices are currently not available within the NFS dataset. The effect of increasing milk yields by improving the breeding index is estimated by regressing the average yield per cow in the dairy herd, on the amount of concentrates, number of days grazed, early/late calving and predicting the error term. The error term captures the variation in milk output unexplained by the observables and we attribute this to variation in the breeding index. The minimum breeding index (as captured by the error term) in the top yield per cow quintile is then taken as the target to be achieved. This error term is substituted instead of the error terms in the lower yield quintile regressions and the new milk yield per cow is predicted. Thus, it is assumed that farms in the lower quintiles are adjusting their breeding index to match the productivity of farms in the upper quintile. This increased yield 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 equations I.1 to I.8. 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. The cost of increasing the breeding index (artificial insemination straws and labour), is taken assuming 4.5 artificial insemination straws per cow at a total cost of €20 per straw (Diskin, 2012).

Assessing the Sensitivity of Model Results

Two sensitivity analyses are conducted to assess whether prevailing market conditions, and farmers output supply/input demand responses influence the relative ranking of the CPUA of measures. In the first sensitivity analysis all quantities (i.e. input and output) are held constant at their 2008 levels and the values of gross output and direct costs are updated by applying historic input and output price indices for the period 1997 to 2009, in the process generating a set of new baseline datasets (one for each year). The seven scenarios discussed earlier are then applied to each baseline dataset and new CPUA for each measure is calculated. This allows one to assess the sensitivity of CPUA ranking to short run changes in prices (i.e. before farms have an opportunity to adjust their decision making). Since input and output quantities are held constant, the change in N produced is not be affected by price changes.

The second, more realistic, sensitivity analysis proceeds by using the actual input and output quantities and prices for each year from 1997 to 2009, capturing both the effects of price changes and the farmers' responses. Once again the CPUA is calculated for the seven scenarios and the consistency of their ranking is explored. In this analysis the changes in quantities will also lead to changes in the level of N produced, in addition to changes due to the seven scenarios.

I.5 Data

In order to simulate the changes at a farm-level, socio-economic data at the farm level is required. Teagasc - The Irish Agriculture and Food Development Authority- has conducted the National Farm Survey (NFS) on an annual basis since 1972 (Connolly et al., 2010). The resultant dataset contains information for a sample of approximately 1,200 farms per annum that are nationally representative of over 100,000 farms in Ireland. This sample, however, excludes pigs and poultry farms due to an inability to obtain a representative sample for these types of farms. It is also not representative of very small farms. The NFS dataset contains socio-economic information which allows analysis of the physical and economic performance of the different farming sectors in the Republic of Ireland to be conducted.

In this paper NFS data for the year 2008 is used for model validation and model extension simulations and NFS 1997 to 2009 is used for sensitivity analysis. Farms in the NFS are assigned to one of six possible systems: specialist dairy; dairying other; cattle rearing; cattle other; mainly sheep; mainly tillage (Hennessy et al., 2010). The category assignment is based on the dominant enterprise, which is established based on the Standard Gross Margins (SGMs) under the EU FADN typology set out in the Commission Decision 78/463 (Hynes et al., 2008, Kinsella and Connolly, 2004). Under this methodology SGM is assigned to each type of farm animal and each hectare of crop. Farms are then classified into groups called particular types and principal types, on the basis of the proportion of the total SGM of the farm which comes from the main enterprises (after which systems are named). This methodology was adapted to suit Irish conditions more closely (the reader is referred to Connolly et al. (2009) for further details). Farms in Ireland typically engage in more than one enterprise.

The number of farms in the NFS sample varies from year to year from 1,279 farms in 1994 to 1,054 in 2009, which reflects the decreasing number of farms in Ireland, however the farms are getting bigger in size and more specialised. National weights are applied to represent the 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 this research the focus is on farms that are identified in the NFS as 'specialist dairy' and 'dairy and other activities' (from now on referred to as dairy). There are two primary reasons for focusing on dairy farms in this research: 1) the relatively good economic performance of dairy farms in Ireland and 2) environmental pressures generally associated with intensive dairy farm systems.

In terms of economic significance, dairy farms in Ireland have gross margins that are high relative to other farm systems and dairy farms' gross margins are growing at a faster rate. Gross Margin (GM) is a good indicator of farm performance because it represents the difference between Gross Output (GO) and Direct Costs (DC). Furthermore, movements in GO (Figure I.3) and DC (Figure I.4) provide useful information about the source of changes in GM (Figure I.5).

Figure I.3. Dynamics of Gross Output on farms in Ireland (1996-2008).

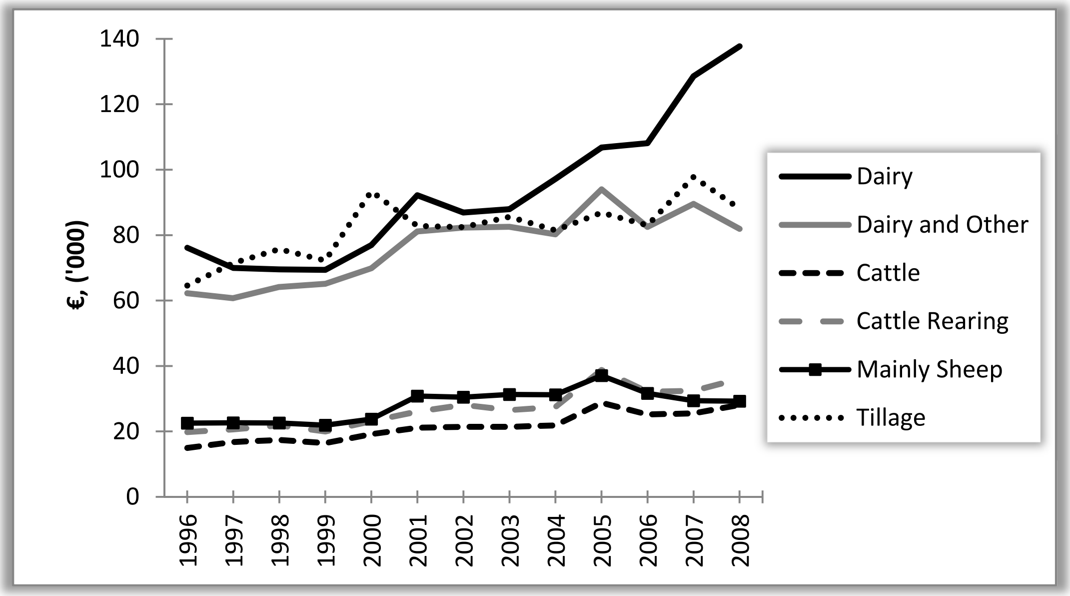


Figure I.4. Dynamics of Direct Costs on farms in Ireland (1996-2008).

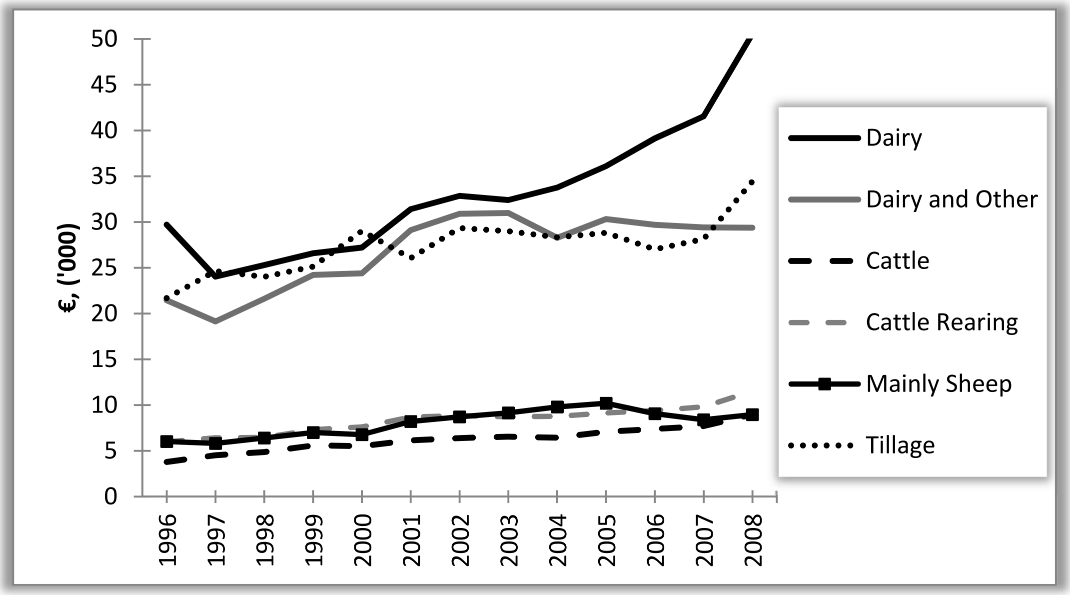
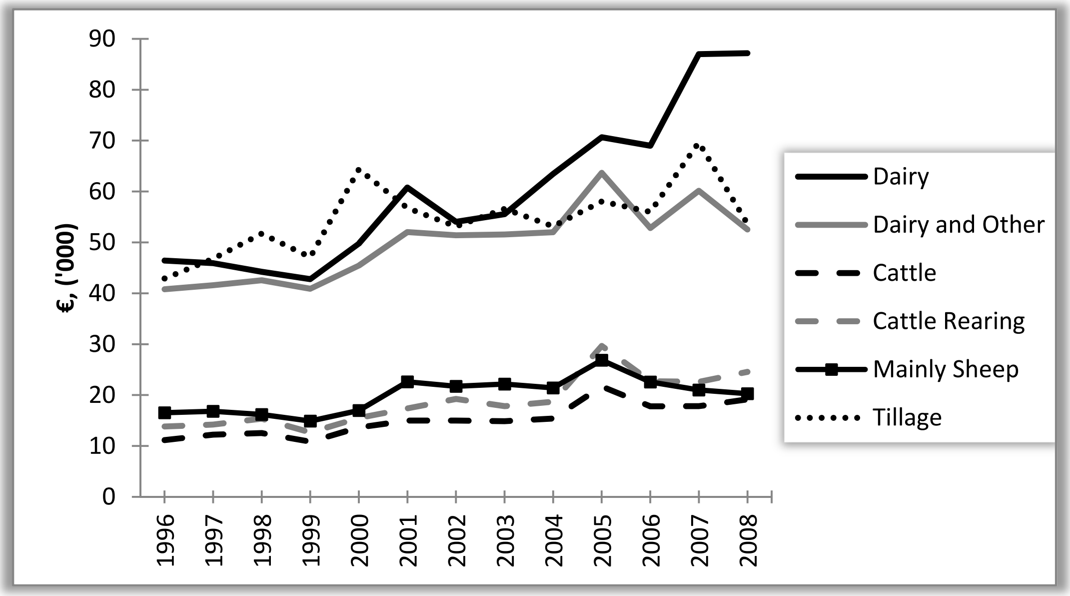


Figure I.5. Dynamics of Gross Margin on farms in Ireland (1996-2008).



It can be seen in Figure I.5 that dairy and dairy other farms have significantly higher GM than cattle, cattle rearing and mainly sheep systems. It is also evident that dairy GM is growing at a rate higher than in other systems during the period. This is due to the high growth rate of dairy output (Figure I.3) despite the fact that for the dairy farms the value of direct costs was growing at the same time (Figure I.4). The rapid growth in dairy farms' GO was caused by both increased milk yield per animal and due to consolidation in the industry with fewer farms producing more milk.

Dairy and dairy other farms are not only leaders in terms of economic performance; they also have higher organic N production and chemical N use per hectare (Table I.4) relative to other systems. The national average (which is lower than the non-derogation requirement of 170 kg N per hectare under European Communities (Good Agricultural Practice for Protection of Waters) Regulations (2010)) disguises the range of organic N application across Irish farms with 27 percent of the farms in Ireland producing more than 170 kg of organic N per hectare. At the moment farmers that are over the requirement of 170 kg of organic N per hectare can apply for derogation, but the regulation may become more stringent in the future.

Table I.4. Mean N per hectare and Proportion of farms in N categories, 2008

Org. N (kg per hectare)				Chemical. N (kg per hectare)			
Farm System	<170	>170	Mean	<226	226-279	>279	Mean
Dairy	0.79	0.21	142	0.92	0.05	0.03	134
Dairy other	0.96	0.04	82	0.99	0.01	0	67
Cattle	0.99	0.01	72	1.00	0	0	40
Cattle rearing	0.99	0.01	79	1.00	0	0	42
Sheep	1.00	0	36	1.00	0	0	36
Tillage	1.00	0	22	0.78	0.01	0.21	62

Source: weighted NFS data, 2008

The dairy system turns out almost twice as much organic and chemical N per hectare as any other system. Dairy other farms, despite reducing N emissions over the previous few years, still report higher amounts than in other systems. Twenty one percent of the dairy farms and four percent of dairy other farms in Ireland in 2008 exceeded the limit of 170 kg N per hectare (Table I.4). Additionally, 3 percent of dairy farms were found to have exceeded chemical N limit per hectare.

GIS Data

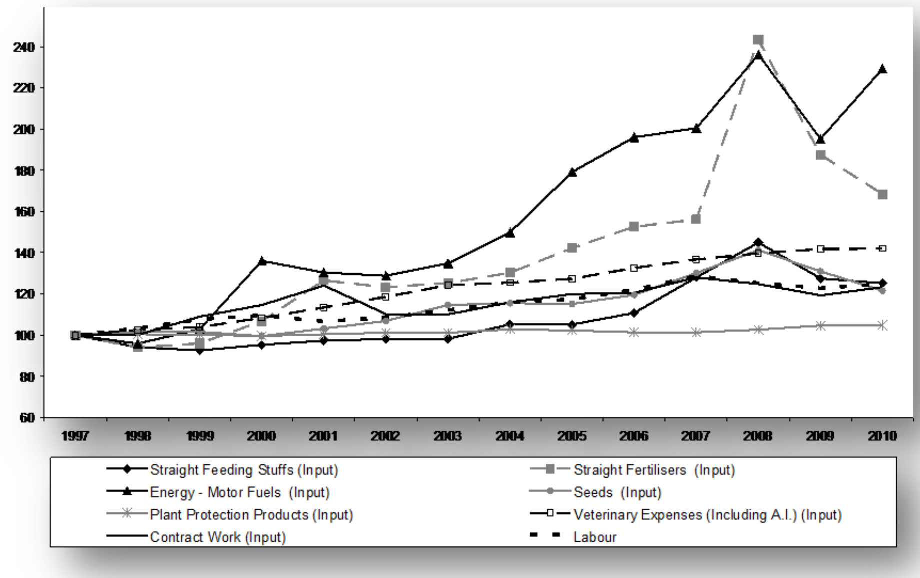
In order to estimate the effect of the stream fencing scenario, information on the number of farms that have streams within 500 meters of the farmhouse was collected. GIS was used to collect these data. Data on the proportion of farmland within a 10m buffer of the river were also obtained specifically for this analysis.

Data on Price indices

In order to account for changes in prices, information on price indices from the CSO is utilised in this paper (Figures I.6 and I.7). To reflect changes in output prices a milk price index, a total cattle price index and a sheep price index from the CSO is used (see Figure I.6). Changes in input prices for direct costs were captured using a ‘straight feeding stuffs’ index for concentrates; an energy price index for transport expenses; a veterinary expenses index for veterinary and medical expenses including AI; a labour index for all labour expenses on the farms and finally an “other products” agricultural CSO index was used for miscellaneous direct costs. Price indexes for winter forage and pasture expenses are not produced by the CSO, so a price index for winter forage and pasture is calculated by taking a weighted sum of the indices for the components of winter forage and pasture, which include fertiliser, crop protection, seeds, machinery hire, transport costs and labour expenses.

As can be seen in Figure I.6, all input prices exhibited an upward trend during the period 1997-2010. Fertiliser and energy prices increased most sharply, reflecting increasing oil prices. For dairy farms in Ireland, fertiliser on average contributed 55 percent of the total expenses for pasture and winter forage so it is not surprising that the prices for straight feeding stuffs follow a similar upward trend to that of fertiliser.

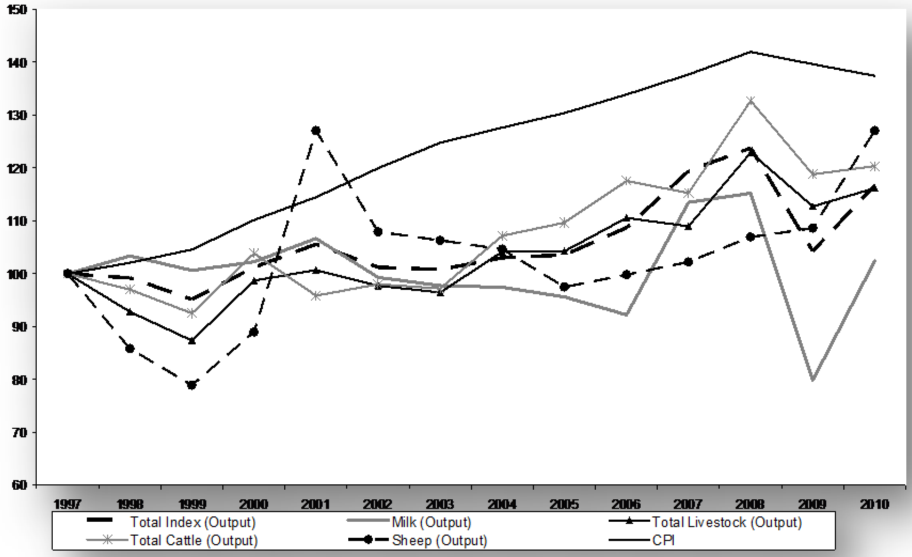
Figure I.6. Agricultural input price indexes (1997-2010)



Note: 1997=100

Figure I.7 illustrates the evolution of agricultural output prices from 1997 to 2010. With the exception of sheep, product prices rose at a rate much lower than the consumer price index (CPI). Moreover the gap between the CPI and agricultural output prices widened during the period.

Figure I.7. Agricultural output price indexes and CPI (1997-2010)



I.6 Results

Model Estimates

Table I.5. Summary Statistics (2008)

	min	mean	max
Farmer's Age	27	52	85
Teagasc client	0	0.7	1
REPS	0	0.3	1
Farm Size (ha)	8.1	50.8	281
Farm GM (€)	8102	87272	589288
Dairy GM (€)	2859	61548	375108
Cattle GM (€)	-5934	11587	107616
Sheep GM (€)	-1514	433	15541
Dairy LU	11	51.2	233
Cattle LU	0	37	272
Sheep LU	0	1.5	63
Dairy Labour per LU (€)	0	6.2	301
Cattle Labour per LU (€)	0	0.3	79
Sheep Labour per LU (€)	0	0.02	9
Dairy Fertiliser (kg/ha)	0	218	682
Cattle Fertiliser (kg/ha)	0	224	736
Sheep Fertiliser (kg/ha)	43	216	850
Dairy Concentrates per LU (€)	26	251	879
Cattle Concentrates per LU (€)	0	165	705
Sheep Concentrates (€)	0	179	14709

Source: Weighted NFS data

The estimates for gross output and direct costs per LU for dairy, beef and sheep enterprises are reported in Table I.6.

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

VARIABLES	Dairy		Cattle		Sheep	
	GO/LU	DC/LU	GO/LU	DC/LU	GO/LU	DC/LU
ln(Farmer's Age)	-0.110** (0.053)	0.0032 (0.105)	-0.035 (0.085)	0.033 (0.115)		
Teagasc client	0.0507* (0.026)	-0.0595 (0.052)	0.0182 (0.042)	-0.0545 (0.058)		
REPS	0.053** (0.026)	-0.024 (0.052)	0.047 (0.042)	-0.0041 (0.058)		
Soil 2	-0.045* (0.026)	-0.015 (0.051)	-0.131*** (0.042)	-0.012 (0.057)	-0.256 (0.234)	-0.289 (0.582)
Soil 3	-0.124** (0.052)	0.0786 (0.102)	-0.0798 (0.081)	-0.0207 (0.111)	-1.420*** (0.296)	1.022 (0.741)
Western Region†	0.183 (0.150)	0.121 (0.293)	-0.131 (0.244)	-0.226 (0.335)	-0.667 (0.704)	1.894 (1.781)
Midlands Region	0.185*** (0.049)	-0.014 (0.095)	-0.076 (0.076)	0.001 (0.104)	-0.428 (0.285)	0.635 (0.722)
Mid-East Region	0.149*** (0.052)	-0.356*** (0.102)	-0.00717 (0.083)	-0.0452 (0.114)	-0.472 (0.490)	-0.111 (1.237)
Dublin Region	0.111** (0.052)	-0.472*** (0.098)	-0.115 (0.078)	0.239** (0.107)	0.082 (0.423)	0.691 (1.078)
South-East Region	0.119*** (0.044)	-0.365*** (0.083)	-0.033 (0.066)	0.108 (0.090)	-0.441* (0.243)	0.727 (0.609)
South-West Region	0.123*** (0.040)	-0.284*** (0.075)	-0.140** (0.060)	0.273*** (0.082)	-0.594** (0.235)	0.601 (0.593)
Mid-West Region	-0.040 (0.0840)	-0.272* (0.164)	0.043 (0.118)	0.0213 (0.162)	-0.898* (0.487)	-3.025** (1.239)
ln(LU)††	0.028 (0.036)	0.155** (0.069)	-0.171*** (0.031)	-0.270*** (0.042)	-0.095 (0.086)	0.701*** (0.202)
ln(Farm Size)	0.0875*** (0.033)	-0.0883 (0.0655)	0.221*** (0.049)	0.166** (0.067)	0.109 (0.192)	-1.240*** (0.447)
ln(Labour/LU) ††	0.0190** (0.009)		0.107* (0.064)		-0.0004 (0.314)	
ln(Concentrates/LU) ††	0.188*** (0.022)		0.121*** (0.020)		0.023 (0.061)	
ln(Fertiliser/ha)††	0.129*** (0.027)	0.054 (0.052)	0.181*** (0.032)	0.281*** (0.043)	-0.101 (0.149)	0.231 (0.374)
Constant	5.527*** (0.296)	5.955*** (0.550)	4.884*** (0.427)	4.423*** (0.585)	6.732*** (0.823)	5.691*** (1.866)
Observations	326	326	351	351	63	63
R-squared	0.457	0.176	0.285	0.279	0.454	0.381

*** significant at 1percent level; ** significant at 5percentlevel; *significant at 10percentlevel
† Boarder Region is a reference region in the regressions; †† enterprise specific

The significance levels of the estimates and the standards error are also reported in Table I.6. Farmer's age is negatively associated with dairy and cattle gross output per LU but has a positive relationship with direct costs per LU. This indicated that younger farmers have higher GO per LU and lower costs per LU, which indicates that they may be able to manage farms more efficiently. Teagasc clients tend to have higher GO and lower DC per LU. This is not surprising as Teagasc clients have access to specialist advisory services. The results of the estimates indicate that those farms that participate in REPS also have higher GO/LU and lower DC/LU. Although Teagasc and REPS estimates are only statistically significant for dairy GO/LU. Soil and region variables are included in the analysis to account to spatial heterogeneity. The number of LU and size of farm are included in the regression analysis to capture economies of scale with the bigger farms normally displaying higher outputs and lower costs per LU. Labour, concentrates and fertiliser used per LU are driving GO per LU up, these are the main inputs into the production on the farm. Fertiliser usage is also positively associated with other direct costs on the farm, which indicates that when farmers use more fertiliser per LU they also tend to use more other inputs per LU.

Model Validation Results.

The results of the validation scenarios are reported in Table I.7. The analysis is focused on the farm GM because it changes in the short run while fixed costs are only adjusted in the long term. Table I.7 presents the farm GM and the enterprise specific GM, GO and DC (with a prefix D representing dairy, C for cattle and S for sheep enterprises) that are anticipated to result under each mitigation scenario. Baseline figures, which reflect the average farm gross margins, gross output and direct costs on the affected farms before simulations, are presented in parentheses. The simulated outcomes suggest that farm gross margin would decline significantly following a reduction of LU by 20 percent, decreasing from €63,867 down to €49,635 – a loss of around €14K on average per farm. Gross margins decline on average across all enterprises, but beef enterprise will be mostly affected. Fezzi et al. (2008), using a farm budgeting model, which is based on similar UK farm data for year 2005, reports an average loss of £166/ha or approximately €244[3]/ha on dairy farms due to this measure, which is broadly consistent with the findings reported here, which is €294 per hectare (17 percent difference with Fezzi et al.).

[3] In 2005, £1 was approximately equivalent to €1.47 (http://www.x-rates.com/average/?from=GBP&to=EUR&year=2005)

Table I.7. Farm and enterprise GM, GO, DC under Each Scenario

Scenario	FGM	DGM	DGO	DDC	CGM	CGO	CDC	SGM	SGO	SDC
Reduce LU 170kg	75116* (81259)†	72962 (73964)	120997 (122776)	48035 (48813)	1983 (7124)	15757 (28623)	13774 (21498)	171 (171)	246 (246)	75 (75)
Reduce LU -20percent	49636** (63867)	43878 (55864)	71460 (89880)	27581 (34016)	5497 (7695)	20572 (24750)	15075 (17054)	260 (306)	553 (676)	293 (370)
*Equivalent per hectare figures – 1687 (1848); **Eqvivalent per hectare figures – 1315 (1021);										

†the baseline amounts are reported in the brackets, the averages are produced for affected farms only (for example, "reduce LU170kg affects only farms that produce more than 170 kg of organic N per hectare")

When the mitigation approach is instead to reduce organic N on the farm to a maximum of 170 kg of organic N per hectare, the GM on the affected farms would decline on average by €6K, or by €161 per hectare. This measure is more likely to affect farms engaged in relatively intensive production with stocking rates close to or over 2 LU per hectare and an average farm GM higher too (Table I.7). This measure affects beef enterprise leading to a loss in beef enterprise GM of €5,141 on average for the dairy and dairy other farms. The underlying assumption here is that the farmers drop the livestock with the lowest GM per animal. Results from the NFS sample in 2008 indicate that beef LU attract on average low GM returns on dairy and dairy other farms in Ireland and hence this enterprise is most affected. One might expect that sheep would be affected, however, as the analysis revealed – only 5 farms out of 323 dairy and dairy other farms in the sample have sheep LU. Beef LU attract lower GM on these farms. Hennessy et al. (2005) simulated the effect of this measure on 2002 data using representative NFS farm for 2008 and their result was a loss between €8,000 and €3,496 in farm profit depending on how much N a farm would need to mitigate to comply with 170 kg of N/ha limit. In the model reported here this measure results in the change of FGM of €6,143 (which is comparable to change in farm profit as stated in equation 4), which falls roughly in the middle of their estimates. Hennessy et al, simulated their results into the future which may lead to differences in estimations, however, the results are quite comparable otherwise.

Table I.8. Percentage Change in Farm and Enterprise GM, GO, DC under Different Scenarios

Scenario	FGM	DGM	DGO	DDC	CGM	CGO	CDC	SGM	SGO	SDC
Reduce LU 170kg	-8	-1	-1	-2	-72	-45	-36	0	0	0
Reduce LU - 20 %	-22	-21	-20	-19	-29	-17	-12	-15	-18	-21

The percentage change in GM, GO and DC as a result of the simulated policy scenarios is reported in Table I.8. Reducing LU to achieve 170 kg organic N per hectare on average yields a decrease in farm GM of 8 percent on affected farms- mostly due to fall in GM from the beef and dairy enterprises (Table I.8). This is despite an associated fall in costs. The results also revealed that not all farms that exceed the 170 kg of organic N per hectare threshold are equally affected.

Twenty five percent of dairy and dairy other farms (approximately 4,242 farms) exceed the limit in 2008 based on the weighted NFS data. If these farms were to reduce their emissions to comply with the stated limit, approximately 90.5 percent of these farms would have a reduction in GM and 9.5 percent would have a gain in GM due to the fact that on some farms the GM from beef cattle is zero or even negative. In Hennessy et al.'s (2005) simulations the projection is that approximately 80 percent of farms would be negatively affected by this measure by 2007 and 88 percent by 2012, thus, their projections slightly underestimated the impact.

If the farmers in Ireland were to reduce their livestock units by 20 percent, their GM per hectare would on average decrease by 22 percent. This measure would negatively affect all farm enterprises (dairy, cattle and sheep) on dairy farms. It is interesting to note here that Fezzi et al. (2008) assumed the 20 percent cost decrease due to this measure in their calculations. They based their assumption on different research papers and expert opinion. Thus, the results of the model developed here confirm their assumptions. It has to be noted that reducing LU by 20 percent would not only lead to a loss of output squeezing already narrow farm margins, but would also be inconsistent with the Food Harvest 2020 agenda, an Irish policy, which requires the growth of agricultural output by about 33 percent (Food Harvest 2020).

Farm N implications under each model validation scenario

The potential N reduction that would result from the mitigation measures would have important environmental implications. Both measures offer the potential for N reduction on the farms in the form of organic N reductions (i.e. less manure). Table I.9 summarises the amount of organic N on the farms under the two case study scenarios and the percentage changes that would be anticipated. A relatively high organic N reduction (20 percent) can be achieved by reducing the number of LU by 20 percent on Irish dairy and dairy other farms; under the LU reduction to achieve 170 kg organic N per hectare on average 18 percent of organic N can be mitigated on affected farms, or 5 percent on average across all dairy and dairy other farms (Table I.9).

Table I.9. Changes in N per hectare under Different Scenarios

Scenario	OrgN	
	Kg/ha	%
Reduce LU to 170kg N Per hectare	164 (200)*	-18
Reduce LU by 20%	115 (144)*	-20

*the baseline amounts of organic N per hectare

Table I.10. The average cost of mitigation measures

Scenario	€/N
Reduce LU to 170kg N Per hectare	4.5
Reduce LU by 20%	10

In order to compare the measures, the average cost per unit of N abated through each measure is presented in Table I.10. The average cost per unit N reduced in the scenario reducing LU by 20 percent measure is €10 while the cost of complying with the organic N limits is €4.5 per unit of N abated. However, the latter offers relatively small opportunities for N mitigation (20 percent versus 5 percent). These reductions translate into 26,162 tonnes of organic N abated at a cost of approximately €261 million for the scenario with LU reduction by 20 percent and 5,740 tonnes of N mitigated at a cost of almost €26 million if the target of no more than 170 kg of organic N per hectare was enforced on the dairy and dairy other farms in Ireland. Thus, if specific targets for N reductions were to be introduced, farmers may need to introduce a combination of different measures in order to achieve the targets. The costs of a combination of methods could potentially be higher and are more difficult to assess.

Model Extensions Results

Estimates for higher yield dairy cows scenario

The breeding index of the dairy herds is not collected as part of the NFS data, thus, it had to be estimated using an OLS (Ordinary Least Squares) regression as discussed above, where the breeding index constitutes part of the residual. The results of the OLS estimations for the higher yielding dairy scenario are reported in Table I.11. The dependent variable is the log of milk output in litres of milk 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 percent 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. The number of calves per cow proved to be statistically insignificant but was retained in the regression as a proxy for cow fertility.

Table I.11. Results of "Higher yielding dairy cows breeding index" estimations.

Ln(milk output/cow)	β
Concentrates/cow	0.0003*** (0.00003)
$(\text{Concentrates/cow})^2$	$-1.96\text{x}10^{-8}$ $(2.32\text{x}10^{-9})$***
Early Calving	0.0721*** (0.02532)
Calves/cow	0.4322 (0.2836)
$(\text{Calves/cow})^2$	-0.1711 (0.1113)
Constant	7.9735*** (0.1752)

*** significant at 1percent level; ** significant at 5percent level; *significant at 10 percent level

Simulated Results

Gross margin and net margin analysis of mitigation strategies

Results for changes in the farm level gross margin per hectare are reported in Table I.12. Gross margin per hectare declines on average for the subset of affected farms under most of the strategies with the exception of the improved breeding index scenario for which the GM per hectare increases from €1,203 to €1,294 (7.6 percent) and the two slurry application scenarios under which farm GM increases from €1,315 to €1,319, €1,315.13 per hectare (0.3 percent, 0.01 percent) respectively. The overall trend reflects the fact that the proposed mitigation measures will generally affect either the scale of production or will increase the costs of production resulting in lower gross margins on dairy farms. Only the strategies that increase production and/or cost efficiency yield positive economic results.

The highest negative impact is observed under the reduce LU by 20 percent scenario, with fencing-off (de-intensification) scenario yielding second highest negative result (projected loss is 22 and 8.7 percent respectively) (Table I.12).

Table I.12. Effect on Farm Gross Margin (€/ha,%) under each mitigation strategy

Scenario	FGM, €/ha	ΔFGM,%
Baseline	1315	
Fert-20%	1265	-3.8
ReduceLU-20%	1021	-22.3
Feed change	1256	-4.5
Slurry 1*	1319	0.3
Slurry 2**	1315	0.01
Baseline	1848	
Reduce LU 170kg	1688	-8.7
Baseline	1373	
Fencing-off (intensif)	1313	-4.4
Fencing-off (deintensif)	1269	-7.6
Baseline	1203	
Breeding Index	1294	7.6

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

A change in feed composition leads on average to a loss of €59 (4.5 percent reduction) per hectare this is due to assumed increases in feed cost which increase the direct costs on the farms. Reducing fertiliser by 20 percent leads to a loss of €50 per hectare (3.8 percent). Fezzi et al. (2008) also explored the cost of reducing the amount of fertiliser by 20 percent. Their result is reduction of GM on dairy farms by £132 per hectare (approximately €194). This result is higher than in the model presented here. However, in their paper Fezzi et al. (2008) state that in another UK study by Cuttle et al. (2007) the cost of this measure is much lower - £35 per hectare (approximately €51), which is very close to the result reported in Table I.12. Fezzi et al. (2008) attribute the differences between their results and that of Cuttle et al. (2007) to the differences in assumptions used in the two models. This could also be the case here; however, the differences could also be attributed to the differences in the farm data and prices. Fencing off streams results in a loss of €104 (7.6 percent reduction) per hectare on affected farms if the farmers reduce stocking rates proportionally to the reduction in land farmed. However, if the farmers decide to keep their stocking numbers and intensify the production on the remaining land the loss can be mostly offset – reducing to €60 per hectare (4.4 percent reduction). However, this may mean that environmental objectives are not then being met.

Farmers may be more concerned with how the mitigation measures would affect Farm Net Margin (FNM) rather than GM. FNM is GM less overhead costs, which can be substantial on the farms. The effect of the measures on the FNM is reported in Table I.13. The effect on FNM and FNM per hectare is more dramatic than that on the GM. The reduction in LU by 20 percent potentially leads to FNM reduction from €441 per hectare to €147 per hectare, which translates into 63 percent reduction in FNM/ha due to this measure. Reducing LU to achieve 170 kg of N per hectare leads to a FNM/ha loss of almost 24 percent and fencing off stream leads to a loss of 23 percent of FNM/ha on average per farm. Changing the breeding index leads to gains in FNM, however, the initial investment could be high and is not taken into account here due to uncertainty regarding the costs.

Table I.13. Effect of the N Mitigation Measures on Farm Net Margin and Farm Net Margin per hectare

Scenario	FNM/ha	FNM
Baseline	441	21,066
Fert -20%	391	18,701
Reduce LU -20%	147	6,835
Feed change	381	18,364
Slurry 1*	444	21,232
Slurry 2**	441	21,072
Baseline	679	28,754
Reduce LU 170kg	519	22,611
Baseline	458	22,080
Fencing-off (intensif)	398	19,871
Fencing-off (de-intensif)	354	17,768
Baseline	377	16,715
Breeding Index	548	23,591

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

Farm N implications of mitigation strategies

Table I.14 summarises the amount of organic, chemical and total N per hectare on the affected farms under each scenario and the percentage changes from the baseline. All scenarios produce a reduction in total N (except for the case of intensification of production after fencing off streams, when N per hectare on the farms is expected to increase and, thus, cannot be considered a mitigation option); however, some options result in larger total N per hectare reduction than others. Relatively high total N reduction can be achieved by reducing chemical N fertilizer application by 20 percent (12 percent N reduction) and decreasing the number of LU by 20 percent (7.9 percent N reduction). Increasing the breeding index of dairy animals would allow farmers to abate 3.9 percent of total N on affected farms. Under the LU reduction to 170kg N per hectare strategy, on average 17.7 percent organic N can be mitigated. However, the cost of abating N under the different strategies varies across farms. This is discussed in the following sections.

Table I.14. Average farm N under different scenarios (kg/ha;%)

Scenario	OrgN		ChemN		TotalN	
	kg/ha	%	kg/ha	%	kg/ha	%
Baseline	143.8	-	220.1	-	363.9	-
Fert-20%	143.8	0	176.1	-10	319.9	-12
Reduce LU 170kg	136	-5.4	220.1	0	356.1	-2.1
ReduceLU-20%	115	-20	220.1	0	335.1	-7.9
Slurry 1*	143.8	0	218.7	-0.6	362.5	-0.4
Slurry 2**	143.8	0	217	-1.4	360.8	-0.9
Feed change	122.8	-14.6	220.1	0	342.9	-5.8
Baseline	199.3	-	307	-	506.3	-
Reduce LU 170kg	163.9	-17.7	307	0	470.9	-7
Baseline	142.6	-	223.4	-	366	-
Fencing-off (de-intensif)	139.3	-2.3	218.5	-2.2	357.8	-2.2
Baseline	142.3	-	208.6	-	350.9	-
Breeding Index	128.6	-9.6	208.6	0	337.2	-3.9

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

Cost per Unit Abated Results

The changes in economic and/or N per hectare at farm level as reported in Tables I.12 and I.14 do not in themselves allow for cost-efficiency comparisons. CPUA for each strategy are calculated (except for intensification of farming due to fencing off streams) and reported in Table I.15 for comparison. The results represent the cost in € per kg of N abated per hectare, ranging from a cost of over €10.5 per kg N for the fencing-off (de-intensification) strategy to a saving of €5.5 per kg N for the improved cow breeding index strategy.

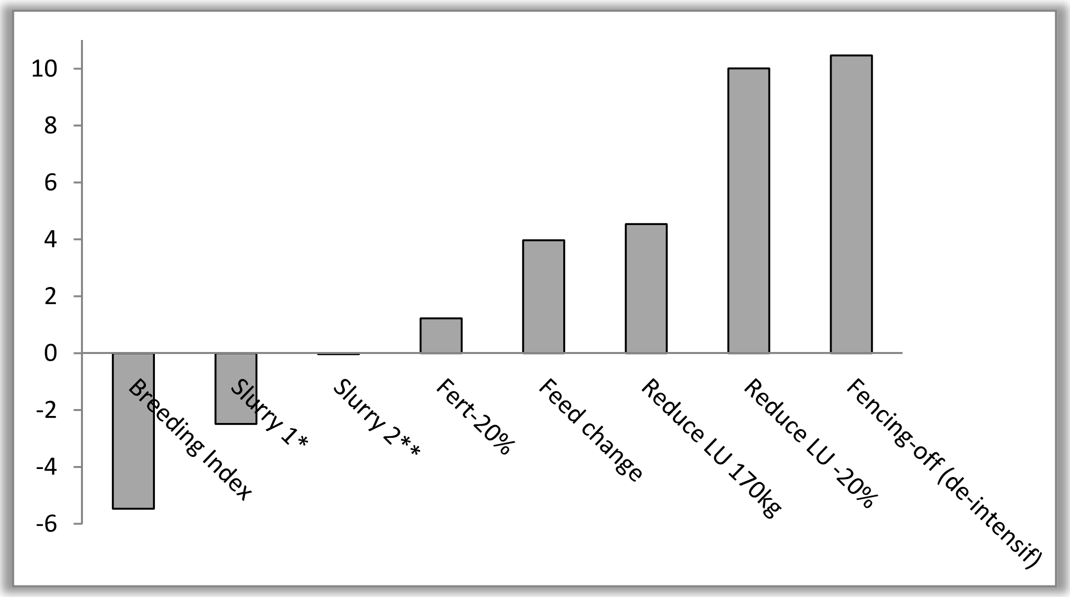
Table I.15. Cost per Unit Abated by scenario

Scenario	Cost (€ per kg N Ha-1)
Fert-20%	1.22
Reduce LU 170kg	4.5
Reduce LU -20%	10
Feed change	4
Fencing-off (de-intensif)	10.5
Slurry 1*	-2.5
Slurry 2**	-0.03
Breeding Index	-5.5

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

The higher the CPUA result, the more expensive it is to abate each unit of total N for farmers. The negative CPUA for the slurry scenarios and the improved breeding index scenario, 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.

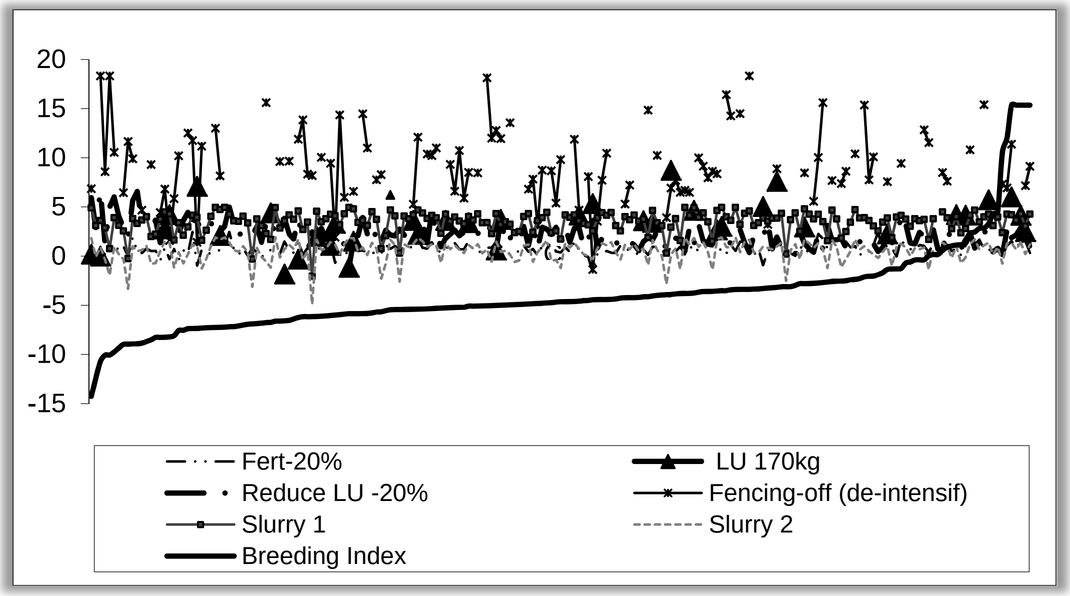
Figure I.8. Ranking of the CPUAs for dairy farms (€/kg N)



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

The ranking of the CPUAs of each mitigation strategy is presented in Figure I.8. Changing the timing or method of slurry application and increasing breeding index of the dairy herd are the most cost-efficient results for N abatement. However, further investigation reveals that country average CPUA numbers hide the diversity of impacts that each strategy would have across individual farms. Figure I.9 shows CPUAs for each strategy for all the individual dairy farms in the NFS sample with farms ranked by the most cost-effective aggregate CPUA – improved breeding index.[4] On Figure I.9 on axis X the farms are ranked starting with the farm that has the lowest CPUA under breeding index scenario and finishing with the farm that has the highest. The costs of the rest of the scenarios are either above or below the breeding index cost.

Figure I.9. Curves for each mitigation strategy for all farms (€/kg N)



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 I.9, the lines cross a number of times indicating different magnitude and ranking of the CPUAs 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.

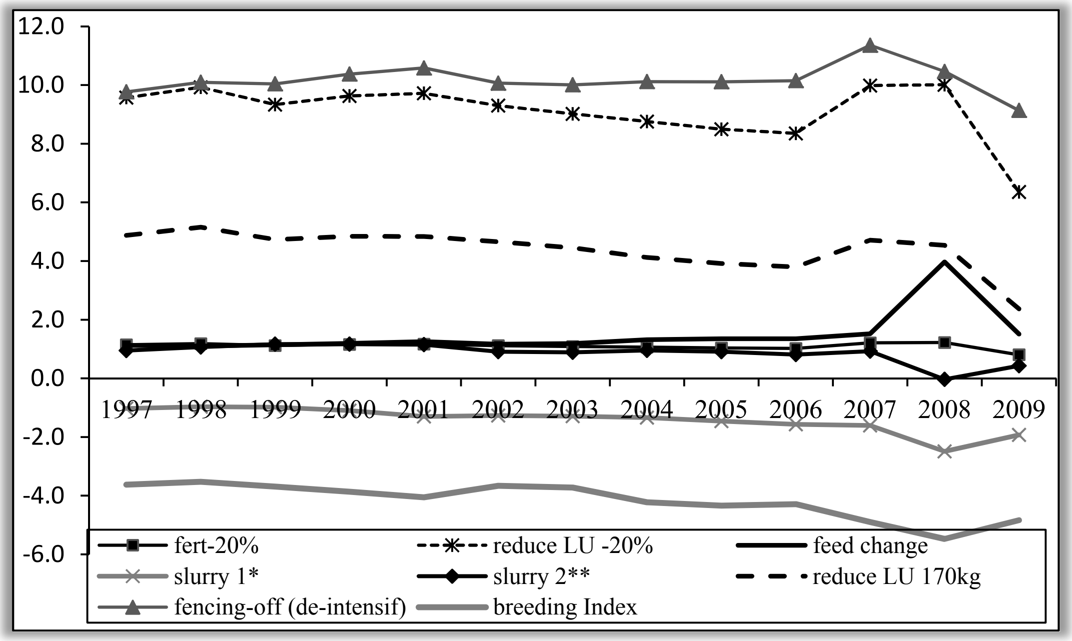
Sensitivity Analysis Results

Figure I.10 displays the results for the first sensitivity analysis, showing the average CPUA for dairy farms for each of the seven policy scenarios while holding quantities constant at 2008 levels and applying prices from the years 1997 to 2009. As can be seen from Figure I.10, the magnitudes of the CPUAs are broadly stable over time up to 2008 and the ranking

[4] Note that in FigureI. 9 some scenarios only affect a subset of farms (e.g. fencing-off) and hence there are breaks in the lines representing these scenarios.

for many of the scenarios is generally consistent. However, in a small number of cases the curves do cross suggesting that price changes that have been experienced in the recent past would have altered the policy recommendation resulting from the CPUA analysis. The relative stability of the CPUAs up to 2008 may offer some comfort to decision-makers regarding the robustness of CPUA analysis to temporary short term price changes which do not result in farmers altering behaviour.[5]

Figure I.10. Average CPUAs with the Price changes holding quantities constant at 2008 levels



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

However in 2009 the large drop in milk output prices leads to substantially lower CPUAs for a number of the scenarios – particularly those involving reductions in livestock numbers. Thus, whilst the CPUA displays some evidence of robustness, nonetheless results may be sensitive to large changes in price levels even when assuming there is no alteration in farmer behaviour (a fairly strict assumption).

When the quantities are kept constant Scenario 7 (breeding index) emerges as the most cost efficient, averaging across all dairy farms. It is possible to say that, on average, two measures are clearly the most "expensive" during this period – Scenario 5 (fencing off the adjacent

[5] The values of the CPUA are displayed in Appendix 1.

streams) and Scenario 3 (reducing LU by 20 percent). The fluctuations of the curves seem to follow the trends in the relevant input/output prices, the cost of the reduction in the dairy LU follows the trend in milk and cattle output prices – going down when these prices go down and going up then these prices go up. Reduction of LU to achieve 170 kg of N per hectare follows the cattle output price trend as this measure would lead to reductions in cattle numbers. The cost of the more efficient slurry application measure seems to slightly fluctuate in the opposite direction to fertiliser prices as would be expected and the improved breeding index scenario reflects the prices on the feeds.

Figure I.11. Changes in CPUA (1997-2009)

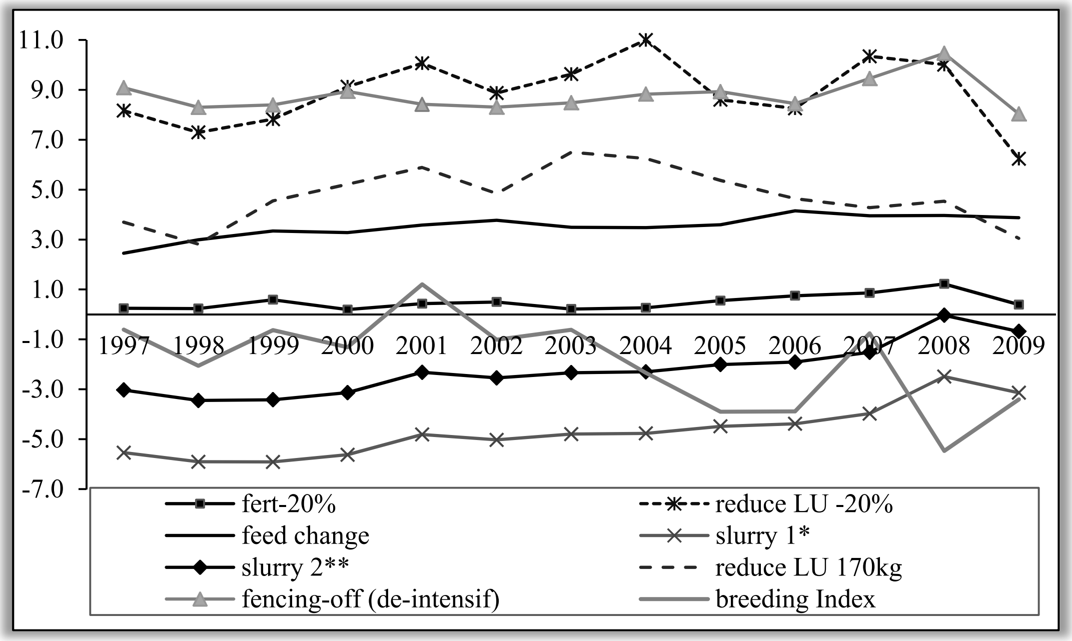


Figure I.11 displays the results for the second sensitivity analysis, showing the average CPUA for dairy farms for each of the seven policy scenarios taking account of changes in production decisions due to price changes. It is immediately evident that the CPUA curves are more volatile as are the ranking of the seven policy scenarios once changes in input and output quantities are accounted for. [6]

Land and fertiliser are the most important inputs into dairy production, hence if these are reduced considerable loss of production and perhaps profits is to be expected. From Figure I.11 it is clear that the most cost efficient measures are the slurry application measures and the increase in higher yielding cows measure (Scenarios 6 and 7). These measures do not

[6] The values of the CPUA are displayed in Appendix 2.

affect the volume of production but make the use of inputs more efficient. Since these measures do not affect the volume of production they may yield multiple-dividends - reduced production costs and reduced negative environmental impacts, i.e. less GHGs emission and less N loss to water streams. However, these approaches tend to lead to relatively small percentage reductions in total N – 3.9 percent from increasing the breeding index and 0.4 percent (slurry 1) from more efficient slurry application suggesting additional measures may be necessary if the N reduction targeted is larger.

From 2002 onwards changing the breeding index offers the lowest CPUA, however between 1997 and 2001 this is not the case. Also the actual CPUA of the two lowest cost abatement approaches (Scenarios 6 and 7) also exhibit considerable volatility during the period which has implications for inferences regarding the total cost of abatement. Thus, not only is the optimal policy instrument likely to fluctuate according to prevailing market conditions and farmers' responses but so too is the cost of abatement. The ranking of the most expensive abatement options (Scenarios 3 and 5) also fluctuates over time although the changes in the level of CPUA are less dramatic. The results support the hypothesis that the ranking of the CPUA is sensitive to changes in prices and to farmers' production decisions and thus, while the CPUA methodology has proven to be a helpful tool in informing policy making, a degree of caution is advisable when presented with a CPUA analysis based on currently prevailing market conditions. Sensitivity analysis based on historic farm behaviour and/or anticipated future market conditions should be routinely carried out to assess whether the policy choice is robust to other market conditions or that the policy itself is designed to be flexible in the face of changing conditions.

I.7 Discussion and Conclusion

Of all human-derived N emissions, agriculture is the most significant single cause for current high N levels in the biosphere. Unfortunately the impressive advance in agricultural productivity has come at a high price in terms of environmental degradation. For instance, N losses from the agricultural sector have been held as a contributory factor behind soil and water acidification, contamination of surface and groundwater resources and loss of biodiversity (Knudsen et al., 2006). Truly sustainable agricultural production will require countries to achieve the twin goals of meeting the growing demand for agricultural produce while also reducing negative environmental impacts from the agricultural production process. The initial policy objective to protect drinking water quality had to be extended over recent decades to account for the damage caused to the environment by excess N compounds. This is reflected in new thresholds for ground- and surface water N concentrations, which have evolved from simple parameter limits to more complex water quality parameters which reflect hydrological, hydro-geological, hydro-morphological and biological properties as enshrined in the EU Water Framework Directive (Directive 2000/60/EC). There are now a wide range of farm management measures which can be employed to reduce N pollution. However, the impact of these measures must be considered before any policy recommendations can be made.

From an environmental point of view a wide range of N mitigation options are available to decision-makers in designing rational economic responses to the continuous pressure to reduce N losses from farmed land. A plethora of research exists which describe different mitigation options to reduce N losses to watercourses from agricultural land (Byström, 1998, Cuttle et al., 2007, Novotny, 2003, Ritter and Shirmohammadi, 2000, Velthof et al., 2009). However, there is a great deal of uncertainty regarding the economic impacts that these measures would have on individual economic agents and on farm incomes in particular. In this paper a microsimulation model that would help to asses such impacts is developed. Initially, a case study analysis of two mitigation measures is explored namely: 1) a stocking rate reduction to achieve a maximum level of organic N of 170 kg per hectare; 2) a 20 percent livestock reduction. Both measures discussed could potentially lead to a reduction in N loss from agricultural land. These measures were chosen as they have been the basis of previous studies using other microsimulation models, thus, are suitable for assessing the consistency of the model specification with the existing research literature. The results are compared in detail to the results by Fezzi et al. (2008) for a 20 percent LU reduction and Hennessy et al. (2005) for a LU reduction to achieve 170kg of organic N per hectare scenario; however, where appropriate, other similar studies are also mentioned.

The results of the model described in this paper are consistent with those previously obtained by Lally et al. (2009), Fezzi et al. (2008) and Hennessy et al. (2005) and confirm that the measures would lead to a reduction in farm gross margins if introduced. In addition the model developed in this paper allows the volume of N mitigated to be assessed and hence an average cost per unit of N mitigated to be calculated.

The model is then further extended to seven potential strategies for N reduction at the farm scale. All of the mitigation options discussed in this paper 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 through a reduction in N application without affecting output. However, it should be noted that this analysis explored N reduction at a farm scale and the subsequent cost to the affected farmer and does not explore the environmental benefit of these measures. It does not follow that all reductions in N at the farm level would be fully realized as benefits to the local aquatic environment. The relationship between the inputs and losses of N may not be linear and may differ spatially, seasonally and be weather dependent; also N losses may happen due to poor management rather than the actual quantities of N used on the farm. Notwithstanding this, it is anticipated that proportional reduction of losses would happen as N that is not introduced to the environment cannot be lost. The environmental effectiveness of the measures would be dependent on a range of local bio-physical conditions including soils and hydrological pathways (Jordan et al., 2012). This paper concentrated on the cost of seven potential N reduction strategies but an overall environmental effectiveness of these measures would require an integrated economic and hydrological approach (Fezzi et al., 2010).

The 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 scenarios except in the higher yielding dairy cows (increase of 7.6 percent) and the two slurry scenarios (increases of 0.3 percent, 0.01 percent), which allow efficiency gain on the farms. These findings are consistent with those of Hennessy et al., (2005) and Fezzi et al. (2008), whose studies also found that the measures that would require livestock reduction would lead to a loss in farm gross margins. These three cost reducing measures can potentially represent a win-win scenario of increased returns to production while reduced risk of N loss. The smallest loss (3.8 percent) in the farm GM per hectare was produced by the 20 percent fertiliser reduction scenario. The largest decline in farm GM per hectare is observed under the 20 percent reduction in livestock numbers scenario at 22 percent. If farmers were to use a lower N feed composition in an effort to decrease N excreted by the dairy cattle, they would experience on average 4.5 percent decline in the dairy enterprise GM, which would be due to a 25 percent increase in feed costs, thus the cost of this measure is dependent on the feed prices prevailing on the market.

Increasing the breeding index of dairy cows can potentially allow the achieving of higher milk yields per animal and, thus, reducing the herd size without the loss of output. This would produce a 7.6 percent increase in the enterprise GM due to the direct cost reduction associated with the reduction in animal numbers. However, it has to be noted that due to data limitations a number of assumptions were made in modelling this scenario. Extending this scenario to a bio-economic model would allow better predictions of the impacts of this measure on the farm incomes.

All the mitigation measure produce a reduction in total N, however, some allow for higher total N reduction than others. Relatively high total N reduction can be achieved by reducing fertilizer application by 20 percent and decreasing the number of LU by 20 percent - 12 percent and 7.9 percent respectively. Increasing the breeding index of dairy animals would allow farmers to abate 3.9 percent of total N.

CPUA analysis indicates that a number of the mitigation measures (changing season or method 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 measures with the largest average CPUA were LU reduction by 20 percent and fencing of watercourses, caused by the large abatement costs associated with these measures as the higher the positive CPUA the more expensive it is to abate each unit of total N for farmers.

The analysis of CPUAs ranking at individual farm level indicates that no strategy is strictly dominant for all farms across the sample. Individual farms have their own CPUA ranking of the measures. Therefore the mitigation strategy that is the most cost-effective at the aggregate level may not be the most cost-effective 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.

CPUA analysis is now widely used to assess the merits or otherwise of various policy options for reducing harmful emissions from agriculture both for human health and the environment (Blok et al., 2001b, Dominic et al., 2009, Moran et al., 2008). Growing population and income in emerging and developing countries will add significantly to the demand for agricultural commodities in the coming decades (Fao et al., 2011). At this stage, it is unclear how elastic the supply response from the agricultural sector will be in response to this increase in demand but it seems highly probable that there will be some impact on price. Biofuel demand could also affect the supply of agricultural goods and hence increase price. On the cost side, there are a number of external factors that could significantly impact farm production and hence the price of agricultural commodities. For instance, agricultural commodity prices are becoming increasingly connected with oil prices and furthermore climate change could also lead to more extreme weather events such as droughts, heat waves and floods which can threaten supply and in turn affect food prices. One issue that is frequently overlooked in CPUA analysis is the sensitivity of the results to changes in input and output prices. The research conducted in this paper has demonstrated that given farm heterogeneity it is important to tailor packages of mitigation measures at the individual farmer. Using microsimulation techniques the current study examined the sensitivity of CPUA ranking of seven N mitigation measures to changes in agricultural input and output prices and finds that CPUA curves and their ranking across the difference scenarios are sensitive to input and output prices.

A major limitation of the model described in this paper is that it does not presently allow for a combination of the mitigation measures to be considered - this may be needed if specific N reduction targets are to be introduced. As a static model, it does not allow for dynamics in farmers' behaviour. Thus, further extensions to the model are necessary to improve the model's capabilities.

The results of the case study scenarios reported in this paper should be interpreted with care as the results of the model are conditional on the validity of the assumptions underlined. The presented results are average results for all dairy farms in the country and hence may obscure differences in the impacts of the considered N mitigation measures for individual farms. Notwithstanding these cautionary remarks, the model represents a considerable advance in determining the costs and other impacts of the mitigation measures.

Given the dynamic nature of the agricultural sector flexibility will be crucial when it comes to formulating farm management actions to reduce N pollution. Policy should not only be targeted at the individual farm level to account for farm heterogeneity, but should also be designed in a flexible manner in recognition of the impacts of changes in agricultural input/output prices. Thus, policy-makers who must choose a particular policy response based on an CPUA analysis should be cognizant of the extent to which changes in commodity prices can alter the conclusions of their analysis and hence the optimal policy instrument. This may in fact require that policy instruments be flexible as rigid regulations may lead to an inefficient allocation of resources and loss of income for the farming community. A more flexible set of policy instruments may increase efficiency while maximising the achievable pollution reduction.

I.8 Appendix 1.

Table I.16. CPUA of N reduction measures (1997-2009) Constant Q

	fert-20%	reduce LU -20%	feed change	slurry 1*	slurry 2**	reduce LU 170kg	fencing-off (de-intensif)	breeding Index
1997	1.1	9.6	1.1	-1.0	0.9	4.9	9.8	-3.6
1998	1.2	9.9	1.1	-1.0	1.1	5.2	10.1	-3.5
1999	1.1	9.3	1.1	-1.0	1.2	4.7	10.0	-3.7
2000	1.2	9.6	1.2	-1.1	1.2	4.8	10.4	-3.9
2001	1.2	9.7	1.3	-1.3	1.1	4.8	10.6	-4.1
2002	1.1	9.3	1.2	-1.3	0.9	4.7	10.1	-3.7
2003	1.1	9.0	1.2	-1.3	0.9	4.5	10.0	-3.7
2004	1.1	8.8	1.3	-1.3	1.0	4.1	10.1	-4.2
2005	1.0	8.5	1.4	-1.5	0.9	3.9	10.1	-4.3
2006	1.0	8.4	1.4	-1.6	0.8	3.8	10.2	-4.3
2007	1.2	10.0	1.5	-1.6	0.9	4.7	11.4	-4.9
2008	1.2	10.0	4.0	-2.5	0.0	4.5	10.5	-5.5
2009	0.8	6.4	1.5	-1.9	0.4	2.4	9.1	-4.8

Table I.17. Apendix 2.

Table I.18. CPUA of N reduction measures (1997-2009)

	fert-20%	reduce LU -20%	feed change	slurry 1*	slurry 2**	reduce LU 170kg	fencing-off (de-intensif)	breeding Index
1997	0.2	8.2	2.5	-5.5	-3.0	3.7	9.1	-0.6
1998	0.2	7.3	3.0	-5.9	-3.4	2.8	8.3	-2.1
1999	0.6	7.8	3.3	-5.9	-3.4	4.5	8.4	-0.6
2000	0.2	9.1	3.3	-5.6	-3.1	5.2	8.9	-1.3
2001	0.4	10.1	3.6	-4.8	-2.3	5.9	8.4	1.2
2002	0.5	8.9	3.8	-5.0	-2.5	4.8	8.3	-1.0
2003	0.2	9.6	3.5	-4.8	-2.3	6.5	8.5	-0.6
2004	0.3	11.0	3.5	-4.8	-2.3	6.3	8.8	-2.3
2005	0.6	8.6	3.6	-4.5	-2.0	5.4	8.9	-3.9
2006	0.7	8.3	4.2	-4.4	-1.9	4.6	8.4	-3.9
2007	0.9	10.3	4.0	-4.0	-1.5	4.3	9.5	-0.8
2008	1.2	10.0	4.0	-2.5	0.0	4.5	10.5	-5.5
2009	0.4	6.2	3.9	-3.1	-0.7	3.0	8.0	-3.4

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[i] Degrees of freedom in linear models is a number of estimated coefficients TIBSHIRANI, R. J. 2014. Degrees of Freedom and Model Search. *arXiv preprint arXiv:1402.1920*..