Agricultural Systems 184 (2020) 102889

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Analysis of the effect of alternative agri-environmental policy instruments on production performance and nitrogen surplus of representative dairy farms

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A R T I C L E I N F O

Keywords:
Nitrogen surplus
Mathematical programming
Cluster analysis
Dairy farms
Agri-environmental policy

A B S T R A C T

Nitrogen (N) surplus is an important environmental problem on the island of Ireland (Northern Ireland and the Republic of Ireland), and the dairy sector has been identified as contributing more to this problem compared to other agricultural sectors. As a result, there has been increased demand for efficient policy measures to improve the economic and environmental performance of dairy farms in the region. In this study, we employed the positive mathematical programming (PMP) optimization modelling framework to simulate the economic and environmental impact of two alternative agri-environmental policy instruments on different dairy farm types. Specifically, the study considers the effects of an N surplus tax and an agri-environmental nutrient application standard on the production performance and N surplus of representative dairy farms using scenario analyses. The results of the analyses showed that the effects of the agri-environmental policy instruments vary across the two countries and clusters of dairy farms, resulting in clear differential effects on farm structure and N surpluses. The study concluded that in situations where the nutrient surplus is already high, as with the large farms clusters in this study, the use of manure application standards will be more effective in limiting nutrient surplus to soils compared to the use of nutrient surplus tax.

1. Introduction

The dairy sector compared to other agricultural sectors, contributes significantly to the agricultural economy on the island of Ireland which comprises Northern Ireland and the Republic of Ireland (DAFM, 2017; DAERA, 2017a). Consequently, the abolition of the milk quota system[1] in 2015, has been seen as a good development in terms of expansion of the dairy sector. However, the policy change has resulted in dramatic structural change in the dairy sector which raises some concern from the perspective of the environment. This is because increased dairy herd sizes have the tendency to result in excess nutrients from manure to the soil thereby increasing the risk of damage to water quality. Nitrogen (N) surplus is already a significant environmental issue on the island of Ireland (Adenuga et al., 2018a; Buckley et al., 2016). Further intensification of dairy farms which has historically contributed more to N surplus in the region will therefore put more pressure on the environment.

Already, more than 50% of river water bodies in Northern Ireland and the Republic of Ireland have been classified as 'moderate' or 'poor' quality and agriculture accounts for more than 20% of the incidence of water pollution (Kleinman et al., 2015; Cave and McKibbin, 2016; EPA, 2017; DAERA, 2017b). In fact, the quality of surface waters has remained relatively static in the last few years and the objective of the water framework directives to achieve a 13% improvement in surface water standards between 2010 and 2015 has not been achieved (EPA, 2017).

The inability to meet the water quality target has been attributed in large part to diffuse nutrient run-off from agriculture and domestic wastewater discharge (EPA, 2017). It is worth highlighting that, before the abolition of the milk quota system in 2015, various policies have

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[1] The milk quota system was originally introduced in 1984, as a measure to limit public expenditure on the sector, and to stabilise milk prices and the agricultural income of dairy farmers. This was done by controlling supply of raw milk among member states through quota allocation in which each member states were given a reference quantity and consequently, each producer within a state was in turn given individual reference quantity (Donnellan and Hennessy, 2015).

https://doi.org/10.1016/j.agsy.2020.102889
Received 20 January 2020; Received in revised form 20 May 2020; Accepted 6 June 2020
Available online 20 June 2020
0308-521X/

been formulated at the local, national and EU level as part of the common agricultural policies (CAP) to ensure good water quality and environmental protection. The most prominent of these policies is the Nitrates Directive, which was designed and adopted by the European Commission in 1991 – (Council Directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC)), to reduce nitrate pollution of water resources resulting from agriculture (European Communities, 2000). It is focused mainly on the management of livestock manures and chemical N fertilizers, by setting limits on the amount of livestock manure applied to the land each year. Specifically, it stipulates that "the amount of livestock manure applied in any year to land on a holding, together with that deposited to land by livestock, cannot exceed an amount containing 170 kg N per hectare". It also sets limits on the application of inorganic N fertilizer. However, it is possible that land application of up to 250 kg N/ha/year from grazing livestock manure under certain conditions may be used, if derogation[2] is sought by an individual farmer and granted by the appropriate authority (European Communities, 2000). Other policies of note are the Water Framework Directive (WFD), which seeks to implement new hydrological plans leading to a good ecological status of water bodies and the current CAP in which, subsidies to farmers are conditional on the fulfilment of a set of environmental requirements (Matthews, 2013). While these policies may have contributed to limiting the damage of nutrient surpluses on the environment and on water quality, it is clear that further environmental policies might be required at the national level to control nutrient surpluses from dairy production in the post milk quota era. This is particularly important given the acknowledgement in the literature that the usual voluntary system of managing nutrient surpluses in dairy farms and consequently promote water quality improvement have not provided the desired results (Doole et al., 2013; Bewsell and Brown, 2011; Adenuga et al., 2020).

The objective of this study is to analyse the effect of alternative agri-environmental policy instruments on production performance and N surplus of different dairy farm types on the island of Ireland. To achieve this objective, this study considers two agri-environmental policy instruments using scenario analyses. First, the study considers the effects of an empirically estimated N surplus tax as an economic instrument to internalise N surplus in dairy farms. The application of taxes on nutrient surplus, which encompasses both inputs, organic manure application and chemical fertilizer, rather than nutrient inputs alone, has been determined in the literature to be a better environmental policy to reduce nutrient surplus (Becker and Kleinhanss, 1995). This is because a levy on fertilizer for example might lead to a reduction in the volume of fertilizer usage but will consequently lead to an increase in the use of manure, which leads to an increase in nutrient surplus (Becker and Kleinhanss, 1995). Secondly, the study considers an agri-environmental nutrient application standard in which derogation is abolished, such that all dairy farms are required to limit their manure N application to not more than 170 Kg N per hectare.

This study contributes to the existing literature in two specific ways. First, the study provides the first attempt to analyse the impact of two alternative agri-environmental policy instruments on the production performance and N surplus in different dairy farm types on the island of Ireland using mathematical programming technique. Secondly, unlike previous studies, the value of the N surplus tax incorporated into the optimization model has been empirically estimated rather than making a blank assumption (Adenuga et al., 2019).

The remaining sections of this paper are organised as follows: In Section 2, we describe the methodology and empirical specification of the model, based on positive mathematical programming (PMP). The results of the scenario analyses are reported and discussed in Section 3 while Section 4 concludes the paper with relevant policy recommendations.

2. Methodology

The existence of heterogeneity and differences in aggregation level among dairy farms alongside varying farm objectives implies that responses to policy changes may vary by farm typology. Hence, this study analysis was carried out in two stages. In the first stage, the K-means non-hierarchical iterative clustering technique was employed to categorise dairy farms into three different farm types of relatively homogeneous units for each region of Northern Ireland and the Republic of Ireland. In the second stage, the positive mathematical programming (PMP) modelling technique was used to analyse the impact of two alternative agri-environmental policy instruments on dairy farms in the post milk quota era. The methodology involved setting alternative policy scenarios with a base scenario that is used as a reference point for counterfactual analysis.

2.1. Representative farm types and cluster analysis

Disaggregation of farms into different typologies allows for the simulation of varying responses of farms to policy changes with respect to the observed sources of heterogeneities (Mark and Huber, 2017; Moghaddasi et al., 2009). However, in classifying farms into different typologies, it is essential that the relevant parameters are taken into consideration, as this has the tendency of influencing the interpretation of observed effects of policy changes. On this basis, the K-means cluster analysis has been employed in this study to categorise the dairy farms into different farm types of relatively homogeneous units with respect to their utilisation of production resources, physical size and economic status. The K-means clustering is a non-hierarchical iterative procedure that partitions observations into k groups by minimizing Euclidean distances between them (Tan et al., 2005).

Unlike the hierarchical cluster analysis, the K-means cluster analysis provides the opportunity to pre-determine the final number of clusters needed. The units to be clustered are continually arranged, such that they are clustered in a way that they are as similar as possible within cluster and as different as possible between clusters. The resulting groups identified by this analytical technique represent groups of farms characterized by a similarity in terms of important variables. The three variables considered and used for cluster analysis are milk yield, utilised agricultural area and herd size. The variables are selected based on their importance in driving differences in the profitability and pollution characteristics among individual dairy farms. Also, unlike monetary variables that could change very significantly between years they are relatively stable with respect to the specialised dairy farms and also fit well to the objective of this study in explaining the effect of the policy change on different dairy farm types. Data was obtained from the Teagasc National Farm Survey (NFS) and Farm Business Survey (FBS) with cluster analysis conducted for a sample of 112 and 74 dairy farms for the Republic of Ireland and Northern Ireland respectively. The method of aggregation conforms to Day (1963) aggregation criteria which maintained that aggregation bias is minimised when grouping is done on the basis of technological homogeneity, managerial ability, production level and institutional proportionality. A similar methodology has been employed by Shrestha et al. (2014); Shrestha et al. (2015); Groeneveld et al. (2016).

2.2. Positive mathematical programming model

The Positive Mathematical Programming (PMP) as employed in this study is a comparative static farm level model that maximizes an objective value of a total gross margin function with the restriction that economic, technical, environmental, spatial and policy constraints are respected. It was formalized by Howitt (1995) to overcome the problem of overspecialisation associated with linear programming (LP) models

[2] Derogation is an EU policy (Commission Decision 2011/128/EU) which permit an increase in the amount of grazing livestock manure that may be applied to land from 170 kg N/ha/year up to a limit of 250 kg N/ha/year, for intensive grassland farms which meet certain criteria.

and was first introduced to the literature in the late 1980s (Howitt, 1995; Paris and Arfini, 1995; Paris and Howitt, 1998). Although the structure of the PMP specification takes the form of a mathematical programming model, the main objective of the methodology is to formulate policy recommendations. The model is able to overcome the defects of other mathematical programming models by allowing for the incorporation of *a priori* information from econometric models (Howitt, 1995). Another important advantage of the PMP model over the traditional optimization model is that it is able to calibrate the model exactly to observed values of production output and factor usage with minimal datasets. The PMP model, once calibrated can be used for policy formulation as a predictive tool to investigate farmer behaviour under different conditions.

The calibration of the PMP model is usually in three phases: the first phase is the differential costs recovering phase, followed by the estimation of the non-linear cost function and, finally, the calibration by using a non-constrained production model with non-linear objective function (Howitt, 1995; Arfini et al., 2005). In the first phase, a linear programming problem is solved with the sole purpose of obtaining an accurate and consistent measures of the marginal cost associated with the vector of observed level of activities. Given the LP problem expressed in Eq. (1)

$$Maximize\ \Pi = X_d p_y - X_d p_c$$

Subject to

$$AX_d \leq b\ [\lambda_l]\ \text{(structural constraint)}$$

$$X_d \leq X_d^* + \varepsilon\ [\lambda_d]\ \text{(calibration constraint)}$$

$$X_d > 0\ (\text{non} - \text{negativity assumption}) \quad (1)$$

Where Π is the objective function to be maximised over a vector of decision variables X_d, while p_y and p_c are the marginal revenue and direct variable cost of the production process respectively. A is the matrix of technical coefficients involving the limiting input levels. Parameter b is the vector of production or policy constraints and X_d^* is the vector of observed activity levels. The production constraints refers to the restriction arising from the initial land endowment for the individual farm types why the policy constraints refers to restriction arising as a result of the milk quota and nitrate directives policies. In situation where quota is binding, it restricts the amount of milk that can be produced. However, in situation where the milk quota is not binding, milk production is restricted by land and the N balance requirement (Groeneveld et al., 2016). λ_l and λ_d are the vectors of shadow prices associated with the allocable input of the structural constraint and calibration constraints respectively. Shadow prices (λ_d) associated with the calibration constraints not only capture 'unobserved' costs or misspecification in technology, but rather any type of model misspecification. The following model misspecifications are possible: data errors, aggregation bias, and erroneous price expectations (Hecklei, 1997; Howitt et al., 2012; Paris and Howitt, 1998). The parameter ε is a small number used to decouple the structural and calibration constraints. This is necessary to prevent the model from having degenerate solutions such that during the first stage optimisation, a unique outcome exists for the binding constraints and the partitioned resource matrix.

The second stage deals with the reconstruction of the marginal costs function in which the parameters of non-linear production functions are calibrated using data, optimal solutions, and shadow prices from the first stage. The integration of the marginal costs function with respect to the output variables within the admissible domain will produce the desired total variable costs function. These functions combine to form the non-linear program that produces the base year solution without calibration constraints. The cost function is assumed to be a quadratic function due to its computational simplicity and the fact that there are no strong arguments for other type of functions (Heckelei and Britz, 2005; Heckelei, 2002). The third stage specifies a non-linear programming model using the calibrated functions from the second stage and the base-year data set. The non-linear programming model includes the original constraints except the calibration constraints. The calibrated non-linear programming model is then used for analyses of various agricultural policy scenarios. This is able to reproduce the primal and dual solutions of the first stage LP models (Paris and Arfini, 2000).

2.3. Nitrogen surplus estimation

N surplus was endogenously estimated in the model based on the soil surface balance approach (Eurostat, 2013; Adenuga et al., 2018b). The measure takes into consideration the differences in the production management systems across the dairy farm types. It is estimated as the difference between total N input into the soil and total N output from the soil. N inputs is estimated from chemical fertilizer and manure inputs to the soil while N output is obtained from N contained in harvested and grazed grass and crops. The inputs from chemical fertilizers were obtained directly from farm businesses *via* the Farm Business Survey (FBS) in Northern Ireland and the Teagasc National Farm Survey (NFS) in the Republic of Ireland. The composition and quantities of nutrient in fertilizer applied to land by the farmers are recorded for each dairy farm in the data bases. N inputs from manure in Kg are estimated based on the excretion coefficient for different types of livestock on the farms (Eurostat, 2013; Adenuga et al., 2018b). This involves multiplying standard nutrient excretion coefficients which represent annual average nutrient excretion per head of animal by the annual average population of the different types of livestock on the farm. This therefore include both the slurry and manure spread on grassland.

2.4. Data and empirical specification of the model

The study area is the island of Ireland which comprises the Republic of Ireland and Northern Ireland (Fig. 1). The data set employed for this study were obtained from two different sources, the Teagasc National Farm Survey (NFS, Republic of Ireland) and the Northern Ireland Farm Business Survey (FBS, Northern Ireland). They represent detailed stratified nationally representative random samples of farms surveyed annually. Variables captured in both data sources are directly comparable, given that they are both collected as part of the EU Farm Accountancy Data Network (FADN) requirements. Data used for analysis was averaged over a six-year period of 2009 to 2014 to correct for occasional events.

The objective function of the PMP model maximizes gross margin, which also gives an indication of the change in farm income resulting from changes in agricultural policy. The gross margin is estimated as the difference between total revenue and total variable costs for the farm type. The N surplus serve as the agri-environmental policy variables and its level give an indication of potential leaching to soils and ground water. Important activities were, milk production, purchase and feeding of concentrates feed, grazing by dairy cows, manure application, purchase and application of synthetic fertilizers *etc.*

2.5. Scenarios

Three scenarios have been explored in this study. They include the scenario in which milk quota is abolished (S1), and two alternative agri-environmental policy instruments scenarios (S2 and S3) in which, in addition to milk quota being abolished, policies are put in place to limit the nutrient losses to the soils.

The S1 scenario seeks to determine the impact of the milk quota abolition on different farm types, by comparing the scenario to the base simulation in which milk quota remain in place as a constraint to milk production. The base simulation reflects the economic, structural and environmental situation of the farm before milk quota was abolished in 2015.

The S2 and S3 scenarios are compared to the S1 scenario to show the impact of the alternative agri-environmental policy instruments, making use of the with-and-without principle. In the S2 scenario, in addition to milk quota abolition, it is envisaged that future dairy production policy will include the enforcement of a tax regime on farms

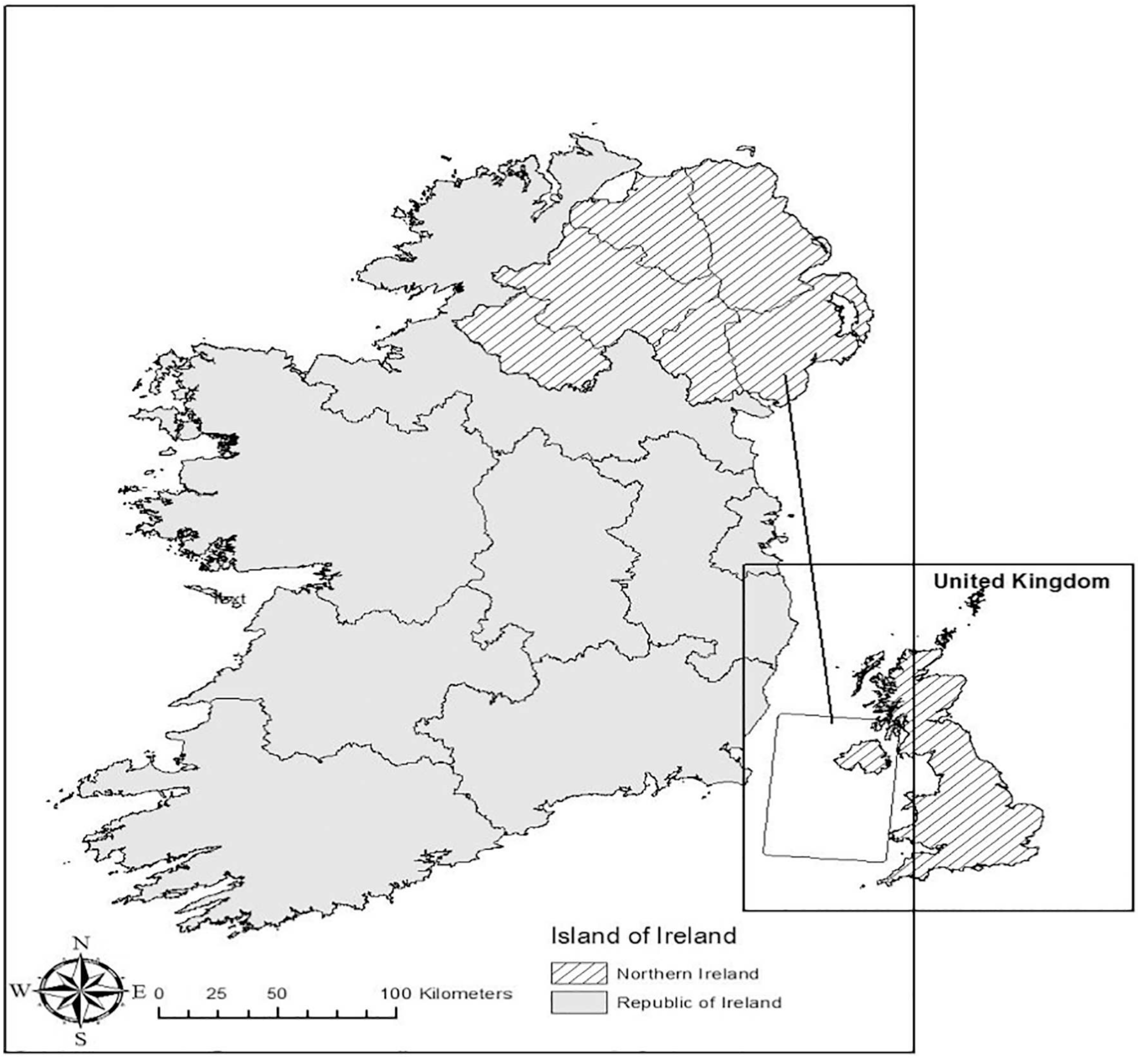

Fig. 1. Map of the study area; inset is the map of the United Kingdom.
Source: Author's compilation.

producing gross N surplus beyond a specific threshold. Two different thresholds have been selected for this study based on the literature (Helming, 1998). These are 170 Kg N/ha (scenario S2a) and 100 Kg N/ha (scenario S2b). Although there is no universally defined level of gross N surplus that meets the European legislation leaching limit of 50 mg/l placed on the levels of nitrate allowable in drinking water, the use of two different thresholds will give a broader view of the likely impact of the N surplus taxation policy. It is also important to note that the relationship between N surplus and the actual leaching of nitrate is not direct as it depends on a range of other biophysical geological and climatic conditions. It is assumed that dairy farmers are required to keep records of nutrient inputs in chemical fertilizer, purchased feed, and manure, and outputs in grass and plant products from their farms from which N surplus per hectare are estimated. Unlike previous studies (Ondersteijn et al., 2003), the values of the tax per Kg of N surplus for Northern Ireland and the Republic of Ireland have been empirically estimated making use of the hyperbolic environmental technology distance function approach. It can be described as the marginal abatement cost for N, with a value of £5.26 (€ 6.2) per Kg for Northern Ireland and €4.02 per Kg for the Republic of Ireland (Adenuga et al., 2019). It should be noted that the tax is applied only to the amount of N surplus above the threshold. If a farm type produces N surplus below the threshold, then the farm is not taxed. In scenario 3, it is envisaged that derogation is abolished and the amount of N from animal manure is limited to the non-derogation limit of 170 Kg N per hectare for the Republic of Ireland

Labour and capital are assumed not to be constraining factors in the model. Farms can rent land only up to a maximum of 20 ha at a cost and prices are exogenous in the model. The limit to the amount of land a dairy farmer can rent represents an estimate obtained from the NFS data based on the average hectares of land that farmers have rented in the past. The relatively small value reflects the limitation in farmers' access to land in the study area. Dairy production is therefore constrained by land availability and dairy quota in the model. The model is run for the average farm for each cluster and shows how each farm will react to the policy changes in a post quota period. Sensitivity analysis was conducted with respect to the effect of changes in milk price on the model outcome. The model was written in the General Algebraic Modelling Systems (GAMS) programming language and was solved using the non-linear solver CONOPT3. A detailed specification of the model is presented in Appendix A.

3. Results and discussion

3.1. Farm types characteristics

A summary of the main production characteristics of the farm clusters in Northern Ireland and the Republic of Ireland is presented in

Table 1
Summary of structural characteristics of the farm clusters in the island of Ireland.

Variables	Republic of Ireland Clusters			Northern Ireland Clusters		
	1 (N = 31)	2 (N = 57)	3 (N = 24)	4 (N = 24)	5 (N = 36)	6 (N = 14)
Grazed grass (kg DM/ha)	7103.1	7231.5	7070.3	6088.0	5531.5	5124.5
Stocking density (LU/ha)	1.96	2.02	2.24	2.03	2.07	2.46
Concentrates (Kg/cow)	836.0	910.5	1416.6	2001.3	2644.3	3790.8
Dairy herd size(numbers)	53.4	63.4	92.6	64.4	94.9	185.8
UAA (ha)	43.8	51.9	70.7	61.3	74.3	116.3
Milk yield (litres/cow)	4119.4	5216.7	6638.6	5155.1	6395.4	8048.4
Chemical N input (Kg N/ha)	139.9	172.2	215.8	134.6	144.0	175.7
Livestock manure N input (Kg N/ha)	141.4	151.7	176.2	149.6	169.4	225.0

Table 1. Based on the results of the cluster analysis, six farm types can be distinguished with three clusters each for the Republic of Ireland and Northern Ireland. The main descriptive statistics for each cluster are shown in Table 1. They represent the average values for all farms in a given cluster. The box plots in Figs. 2 to 4 shows the distributions of all the clusters in respect of the variables used for the cluster analysis to provide a compact view of where the data are centred and how they are distributed over the range of each of the variables. The boxes show medians and quartiles as customary and the added lines are the means of the variables. The graph shows that the milk yield variable tends to completely distinguish between the three clusters in each of the region. The results of a oneway ANOVA analysis conducted for each of the variables shows that on the overall, there exist a statistically significant difference between the three groups in each of the regions with respect to the variables used for cluster analysis.

The majority of the farms fall into cluster 2 and cluster 5 for the Republic of Ireland and Northern Ireland respectively. The farms in these clusters make up about 50% of the total farm population, while farms in cluster 3 and cluster 6 have the lowest percentage of farms in both countries. The cluster 2 and cluster 5 dairy farms can be described as the medium sized farms with an average herd size of 63 dairy cows for the Republic of Ireland and 95 dairy cows for Northern Ireland. On the average, farms in cluster 1 and cluster 4 are the smallest, while farms in cluster 3 and cluster 6 are the largest in terms of herd size and land area. Also, in both countries, farms in cluster 3 and cluster 6 have higher yield per dairy cow but they also have higher concentrate inputs per dairy cow. Generally, dairy farm clusters in Northern Ireland are larger than their respective counterparts in the Republic of Ireland. In terms of nutrient inputs from chemical fertilizer and manure, farms in cluster 3 and 6 are found to have higher N inputs compared to the other clusters. Inputs from chemical fertilizer are generally higher in the Republic of Ireland compared to Northern Ireland. This may be connected to the fact that dairy farms in the Republic of Ireland are more pasture based compared to Northern Ireland and hence the application of more chemical fertilizers. It can be observed in Table 1 that grass grazed per hectare is generally higher in Republic of Ireland compared to Northern Ireland. The stocking density exceeds 2 LU/ha for all three clusters in Northern Ireland and for clusters 2 and 3 for the Republic of Ireland. Farms in cluster 3 and 6 have the highest stocking density in both countries respectively. Manure nutrient inputs per hectare is also found to be higher in Northern Ireland's clusters compared to the corresponding clusters in the Republic of Ireland with the average manure N input exceeding 200 Kg N per hectare in cluster 6 for Northern Ireland.

3.2. Results of scenario analyses

The results of simulating alternative policy scenarios from the PMP model are presented in Tables 2 and 3 for the Republic of Ireland and Tables 4 and 5 for Northern Ireland respectively. The results show that the effects of the milk quota abolition and the suggested environmental policies vary across the two countries and clusters of dairy farms, resulting in clear differential effects on farm structure, gross margin and N surplus. In all three clusters in the Republic of Ireland, an increase in herd size can be observed as a result of the milk quota abolition in the S1 scenario. However, the percentage increase is higher for farms in cluster 3 which also becomes more intensive compared to the other two clusters. This might be connected to the fact that farms in cluster 3 are the larger farm types with higher initial endowment of land and are more commercialised compared to the small sized farms with higher production costs per dairy cow. Groeneveld et al. (2016) also found

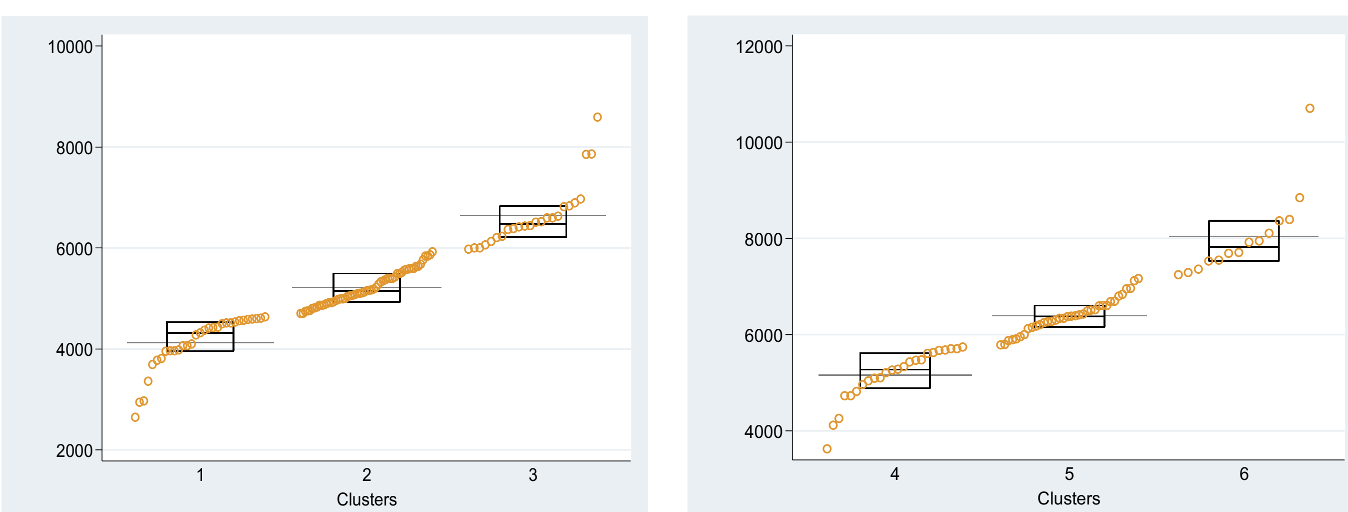

Fig. 2. Box plots showing the distribution clusters in respect of the milk yield variable.

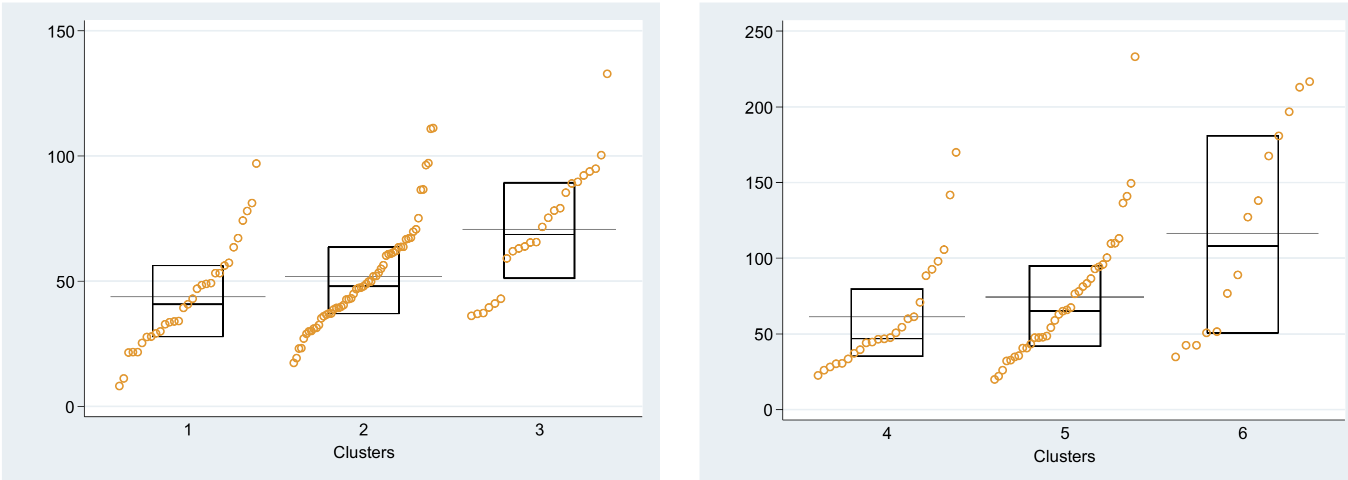

Fig. 3. Box plots showing the distribution clusters in respect of the UAA variable.

similar result in their study in which they stated that smaller farms are less likely to become big and very intensive as a result of milk quota abolition because of higher maintenance costs and relatively lower milk production per cow. The increase in herd size of all clusters results from the fact that milk quota was binding in the Republic of Ireland prior to its abolition in 2015. This result is in line with that of previous studies in which it was found that the abolition of the milk quota system will lead to increase in the size of dairy farms (Sharma et al., 2018; Groeneveld et al., 2016; Boysen et al., 2015; Dillon, 2011; Huettel and Jongeneel, 2011; Louhichi et al., 2010; Klootwijk et al., 2016) and actual data for 2016 which shows an increase in average herd size relative to 2013 (*Central Statistics Office (CSO),* 2016). More extensive comparison of the model results and the actual 2016 data is provided in Appendix B.

An increase in gross margin for all three clusters in the Republic of Ireland can also be observed. However, the percentage increase is higher for the larger dairy farms, ranging from about 3% for the cluster 1 dairy farms to about 30% for the cluster 3 dairy farms. The percentage increase in gross margin for the cluster 2 dairy farms is about 19%. The ability of the larger farms to take advantage of economies of scale may have contributed to the higher percentage increase on gross margin. Similar results were obtained by Groeneveld et al. (2016) for dairy farms in the Netherlands. In the model, the dairy farms in the Republic of Ireland, are able to rent extra land up to 20 ha at a cost to expand their dairy herd size. In the S1 scenario, all three clusters in the region are able to rent the extra land at their disposal to take maximum advantage of the milk quota abolition. This result is line with that obtained by Koeijer et al. (2014) in which they found that the abolition of the milk quota system is likely to lead to increase in the demand for land which might consequently result in a higher price for land.

There is no change in herd size and consequently gross margin for all the clusters of dairy farms in Northern Ireland in the S1 scenario. This is because, the dairy production system in the country was not constrained by quota before its abolition in 2015. It benefited from the flexibility in the management of the UK quota system which gives it access to the single market for milk quota within the constituent countries of the UK. No additional land was therefore required for expansion, such that the extra land is 0 for all the scenarios.

In terms of N surplus per hectare, the abolition of the milk quota system in the S1 scenario will lead to an increase in N surplus per hectare for farms in cluster 3 compared to the base level in the Republic of Ireland. For the dairy farms in cluster 1 and 2, the fact that they were able to rent extra land such that a lower stocking density (number of cows per hectare) is maintained resulted in the N surplus being relatively lower compared to the base scenario. This result implies that access to land will play a vital role in limiting N surplus from dairy production in the post milk quota era.

In the scenario 2 analysis, farms producing N surplus above a specific threshold (Scenario S2a (170 Kg N/ ha) and scenario S2b (100 Kg N/ha) in the S1 scenario are taxed. For the Republic of Ireland, only

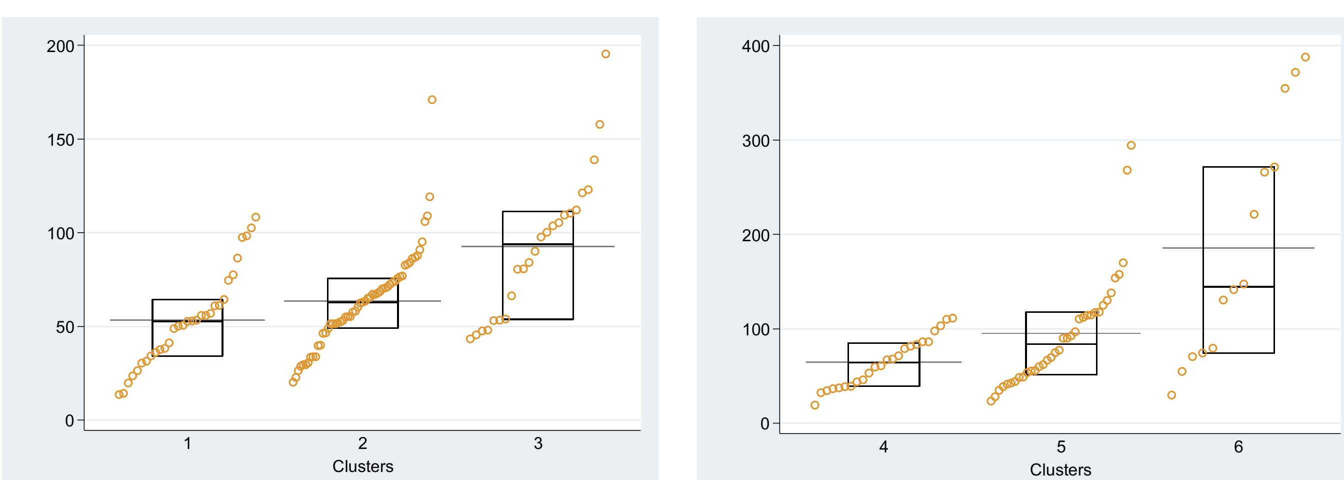

Fig. 4. Box plots showing the distribution clusters in respect of the herd size variable.

Table 2
Effects of policy changes on farm structure and gross margin in cluster 1 and 2 (RoI).

Variables	Cluster 1					Cluster 2				
	Base	S1	S2a	S2b	S3	Base	S1	S2a	S2b	S3
Herd size	53.4	70.1	70.9	71.0	71.4	63.4	84.2	84.9	69.9	84.4
Stocking density (cow/ha)	1.22	1.10	1.25	1.62	1.12	1.22	1.17	1.27	1.34	1.18
Gross margin (€)	30,638	31,716	34,250	38,386	32,291	52,326	62,650	65,327	57,564	62,819
Ext. land(ha)	0	20	13.19	0	20	0	20	13.2	0	20
N surplus (Kg/ha)	98.2	88.6	100.5	130.9	90.3	141.5	135.9	151.4	156.3	136.2

Table 3
Effects of policy changes on farm structure and gross margin in cluster 3 (RoI).

Variables	Base	S1	S2a	S2b	S3
Herd size	92.6	131.3	111.6	88.6	129.7
Stocking density (cow/ha)	1.31	1.45	1.23	1.02	1.43
Gross margin (€)	94,195	122,224	104,908	85,701	120,765
Ext. land(ha)	0	20	20	16.63	20
N surplus (Kg/ha)	207.28	229.68	195.24	160.93	226.77

Base = situation before milk quota is abolished; S1 = milk quota abolition; S2a = tax on N surplus with 170 Kg N/ha threshold; S2b = tax on N surplus with 100 Kg N/ha threshold; S3 = N from animal manure is limited to 170 Kg N/ha.

dairy farms in cluster 3 had N surplus above 170 Kg N/ha, while farms in cluster 2 had N surplus above 100 Kg N/ha and cluster 1 farms had N surplus of less than 100 Kg N/ha. However, for Northern Ireland, all 3 dairy farms clusters have N surplus above 100 Kg/ ha and only farms in cluster 6 have N surplus above 170 Kg/ha (Tables 2–5).

Compared to the S1scenario, an application of the tax policy in scenario 2a resulted in a decrease in the herd size for all clusters in Northern Ireland. Although it was not expected that the herd size for clusters 4 and 5 should fall below the S1scenario given that they did not exceed the threshold in the S1 scenario, the slight decrease in herd size may have resulted from the need to be more careful, given that the N surplus in these two clusters was already on the high side. For the Republic of Ireland, only farms in cluster 3 are affected for the N surplus tax policy when the threshold was 170 Kg N/ha. There is relatively no change in the herd size of farms in cluster 1 and 2 for the Republic of Ireland. This is understandable given that farms in these clusters produces N surplus that is far less than the considered threshold.

In the case of the S2b scenario in which the threshold is reduced to 100 Kg N/ha, a decrease in herd size can be observed for the dairy farms in clusters 2 and 3 for the Republic of Ireland, with a higher decrease in herd size observed for dairy farms in cluster 3 at 17.7% and 20.6% respectively compared to scenario 2a. For Northern Ireland, there is a decrease in herd size for all three farm clusters just like in scenario 2a.

Relative to the S1 scenario, the tax on gross N surplus resulted in a decrease in gross margin for all clusters in Northern Ireland. However, this also leads to a decrease in N surplus compared to the S1 scenario with higher decrease in the S2b scenario compared to the S2a scenario. This result is similar to that obtained by Helming (1998). For the Republic of Ireland, dairy farms in cluster 3 experienced the same effect of reduction in gross margin and N surplus just like farms in in Northern Ireland with respect to scenario 2a and 2b. However, for clusters 1 and 2 a relative increase in N surplus can be observed with increase in gross margin also observed for cluster 1. The implication of this is that, a nutrient surplus taxation policy in the Republic of Ireland will result in a reduction in N surplus and gross margin mainly for the large farms, while the smaller dairy farms are more likely to increase the intensity of their dairy production given that they still have more room before they reach the threshold, beyond which they would be taxed. This result is in line with that obtained by Huettel and Jongeneel (2011) in which they assert that the abolishment of the milk quota regime is likely to affect the future dairy farm size evolution.

In the S3 scenario, results from the Republic of Ireland model shows no significant effect relative to the S1 scenario. This may have resulted from the fact that manure N input in the Republic of Ireland clusters are less than 170 Kg N/ha, except for the cluster 3 dairy farms which is higher. A slight decrease in herd size and N surplus can therefore be observed in the cluster 3 dairy farms compared to the S1 scenario.

The results of the S3 scenario analysis for Northern Ireland showed a significant decrease in the herd size of the cluster 6 dairy farms, while clusters 4 and 5 remain relatively the same when compared to the S1 scenario. A significant decrease in N surplus relative to the S1 scenario can also be observed for the dairy farms in cluster 6 for Northern Ireland. The strict manure policy also resulted in lower gross margin for farms in cluster 3 and 6 respectively in both countries. The result of this scenario is similar to that obtained by Helming and Peerlings (2002) in which they found that the abolition of derogation will lead to decrease in the number of milking cows.

Comparing the results in scenarios S2a to S2b, it can be inferred, that the effect of the taxation policy will depend to a large extent on the threshold of the nutrient surplus and access of the dairy farmers to land. With access to land, the dairy farms can increase herd size without increasing N surplus by renting more land and reducing the livestock density. This, however, will also depend on the price of land. The choice between nutrient surplus taxation policy and application of environmental standards for the control of environmental pressure on land will on the other hand depend on the existing level of nutrient surplus and the dairy production system. In situations where the nutrient surplus is already high, as with the large farm's clusters in this study, the use of manure application standards will be more effective in limiting nutrient surplus to soils. This is because, the large farms being highly commercialised do not significantly reduce their N surplus under the nutrient surplus tax scenario as long as they continue to make profit. This, however, also depends on the amount of the tax and the nutrient surplus

Table 4
Effects of policy changes on farm structure and gross margin in cluster 4 and 5 (NI).

Variables	Cluster 4					Cluster 5				
	Base	S1	S2a	S2b	S3	Base	S1	S2a	S2b	S3
Herd size	64.5	64.5	56.6	53.6	67.8	95.0	95.0	87.9	76.4	97.1
Stocking density (cow/ha)	1.05	1.05	0.92	0.874	1.106	1.28	1.28	1.19	1.029	1.307
Gross margin (€)	46,654	46,654	40,931	38,759	49,047	92,966	92,966	86,112	74,790	94,974
Ext. land(ha)	0	0	0	0	0	0	0	0	0	0
N surplus (Kg/ha)	132.2	132.2	116.2	110.1	139.3	161.5	161.5	149.7	130.0	165.1

Table 5
Effects of policy changes on farm structure and gross margin in cluster 6 (NI).

Variables	Base	S1	S2a	S2b	S3
Herd size	183.9	183.9	164.8	150.9	108.8
Stocking density (cow/ha)	1.60	1.60	1.42	1.298	0.935
Gross margin (€)	199,414	199,414	178,691	163,656	117,907
Ext. land(ha)	0	0	0	0	0
N surplus (Kg/ha)	239.39	239.39	212.44	194.57	140.18

Base = situation before milk quota is abolished; S1 = milk quota abolition; S2a = tax on N surplus with 170 Kg N/ha threshold; S2b = tax on N surplus with 100 Kg N/ha threshold; S3 = N from animal manure is limited to 170 Kg N/ha.

threshold. Similar result was also obtained by Ramilan et al. (2010) in which they found, that environmental standards are more cost-effective than taxes applied to nitrate emissions. With the application of environmental standards rather than increasing intensity of production, the farms will have to purchase or rent additional land to be able to meet the nutrient standard requirement. This result is comparable to that obtained by Hellegers (1996) in which they found that the amount of tax and the level of the tax-free nutrient surplus influences the impact of the nutrient surplus taxation policy. Why we are confident that our model results are valid in the light of the model justification presented in Appendix B, it must be pointed out that this may be only in the short run. This is because the model is a relatively simple model focusing only on some important economic and production variables and assuming that the price of dairy production inputs and outputs are fixed. This is however not usually the case in the long run where for example, the price of milk is volatile such that it changes significantly over time. When this occurs, it could affect the validity of the results.

3.3. Sensitivity analysis

The price of milk is a significant factor in the assessment of the effect of agricultural policy changes on dairy production activities. It is assumed that the expansion of the dairy sector might result in a fall in the price of milk. As a result, sensitivity analysis was conducted by reducing the price of milk by 10%. This is based on the information from literature and current data on changes in milk price (Dillon et al., 2017). All other prices relating to production costs were however kept constant. It is important to note that these prices might also change in the long run and adjustments to price changes is not always instantaneous. The result of the sensitivity analysis is presented in Tables 6 and 7 for the Republic of Ireland and Tables 8 and 9 for Northern Ireland for clusters 1 to 3 and 4 to 5 respectively. A fall in the price of milk by 10% under the sensitivity analysis resulted in small increases in herd size compared to the main analysis. Moreover, unlike before, there is a fall in gross margin, following the abolition of milk quota. This result is in line with the current reality in which a decline in milk price has resulted in a fall in gross margin in spite of increase in dairy production output (Dillon et al., 2017). Nevertheless, the conclusion regarding taxation policies (S2a and S2b) and environmental standards still holds.

An analysis was also performed in which the farms cannot rent additional land when milk quota is abolished for the Republic of

Table 7
Effects of policy changes with 10% price reduction in Cluster 3 (RoI).

Variables	Base	S1	S2a	S2b	S3
Herd size	92.6	111.82	91.4	85.9	109.9
Stocking density (cow/ha)	1.31	1.23	1.145	1.22	1.21
Gross margin (€)	94,195	78,506	68,783	66,051	77,317
Ext. land (ha)	0	20	9.15	0	20.00
N surplus (Kg/ha)	207.3	195.6	181.6	192.8	192.3

Ireland. In this case, it was found that only farms in cluster 3 and 6 increases in herd size by about 16% which is less than the increase of about 30% when the dairy farmers were able to rent additional land. Farms in cluster 2 and 5 remain relatively the same, while farms in cluster 1 and 4 reduced in herd size by about 20%. The reduction in herd size for farms in cluster 1 and 4 must have resulted from the fact that, when land becomes a constraint, it becomes more expensive. In that case, only the most profitable farms (which in this case are the large farms due to being able to take advantage of economies of scale), are more likely to have access to additional land for dairy production while the smaller farms may shrink in size or exit production completely due to competition from the more profitable farms, higher costs of production or a drop in the price of milk. What this imply is that, in situations were no land is available for farmers to rent, the larger farms are more likely to take up land from the smaller farms to be able to expand. This implies that the abolition of the milk quota system without access of the dairy farms to more land will see the large farm sizes getting bigger by taking land from the smaller farm sizes. However, access to land even at a cost means that all the farm type's increases in sizes with the abolition of the milk quota system

4. Conclusion

In this paper a positive mathematical programming (PMP) optimization modelling framework is employed to simulate the effect of alternative agri-environmental policy instruments on the structure and nutrient surpluses of different dairy farm types post milk quota abolition. The dairy farm types can be broadly described as small, medium and large farms types. Three scenarios were considered and analysed to achieve the study objectives. In the first scenario, it was assumed that milk quota is abolished with all other conditions remaining the same. In the second scenario, in addition to milk quota being abolished, dairy farm types producing N surplus beyond a certain threshold are taxed. In the third scenario, alongside milk quota abolition, a limit was set on the maximum N in manure that can be applied to land in line with the nitrates directive assuming that derogation is abolished.

The results of the analyses showed varying effects on the different farm types and across both countries. In specific terms, the abolition of the milk quota system will result in the expansion of the dairy sector in the Republic of Ireland where milk quota was binding prior to its abolition in 2015 but not in Northern Ireland were milk quota was not binding. The level of expansion of the dairy herds in the Republic of Ireland was higher for the large farm types compared to the smaller farm types. The abolition of the milk quota system was also found to

Table 6
Effects of policy changes with 10% price reduction in Cluster 1 and 2 (RoI).

Variables	Cluster 1					Cluster 2				
	Base	S1	S2a	S2b	S3	Base	S1	S2a	S2b	S3
Herd size	53.4	57.7	57.7	55.4	60.2	63.4	71.5	71.5	67.8	72.3
Stocking density (cow/ha)	1.22	1.25	1.319	1.27	1.32	1.22	1.32	1.38	1.31	1.29
Gross margin (€)	30,638	24,006	24,737	24,980	24,981	52,326	44,882	45,621	37,107	44,743
Ext. land (ha)	0	2.30	0	0	1.65	0	2.29	0	0	4.32
N surplus (Kg/ha)	98.2	100.9	106.4	102.1	107.0	141.5	153.0	159.9	151.6	149.2

Table 8
Effects of policy changes with 10% price reduction in Cluster 4 and 5 (NI).

Variables	Cluster 4					Cluster 5				
	Base	S1	S2a	S2b	S3	Base	S1	S2a	S2b	S3
Herd size	64.5	53.7	45.8	42.8	56.5	95.0	79.6	72.6	60.9	81.4
Stocking density (cow/ha)	1.05	0.89	0.78	0.70	0.92	1.28	1.07	0.98	0.82	1.10
Gross margin (€)	46,654	30,940	26,382	24,652	32,547	92,966	63,145	57,585	48,402	64,630
Ext. land (ha)	0	0	0	0	0	0	0	0	0	0
N surplus (Kg/ha)	132.2	110.3	94.1	87.9	116.1	161.5	135.3	123.4	103.7	138.5

Table 9
Effects of policy changes with 10% price reduction in Cluster 6 (NI).

Variables	Base	S1	S2a	S2b	S3
Herd size	183.9	153.5	134.4	120.5	90.8
Stocking density (cow/ha)	1.60	1.32	1.16	1.04	0.781
Gross margin (€)	199,414	132,209	115,746	103,802	78,220
Ext. land (ha)	0	0	0	0	
N surplus (Kg/ha)	239.4	197.9	173.2	155.4	117.1

Base = situation before milk quota is abolished; S1 = milk quota abolition; S2a = tax on N surplus with 170 Kg N/ha threshold; S2b = tax on N surplus with 100 Kg N/ha threshold; S3 = N from animal manure is limited to 170 Kg N/ha.

result in an increase in N surplus per hectare in the large farm types in the Republic of Ireland despite access to extra land due to an increase in dairy farming intensity.

In terms of impact on gross margin, the abolition of the milk quota abolition leads to an increase in gross margin. The percentage increase in gross margin was also found to be higher for the large farm types compared to the smaller farm types. However, a reduction in price of milk by about 10% resulted in a fall in gross margin relative to the base scenario in all farm types.

Based on the two environmental policy scenarios simulated, it was shown that the choice of a tax on N surplus or the enforcements of an application standard as a form of environmental policy instrument on the island of Ireland will depend on the level of N surplus. The clusters of farm types exhibited different responses to the policy changes in both countries. The impact of the policy options was more pronounced in the large farm types with higher N surplus compared to the smaller farm types. The application of N surplus tax resulted in a decrease in herd size and gross margin for the large farm types. The effect was relatively minor for the smaller farm types.

From the results, it can be concluded that land and environmental constraints are likely to be critical factors in the expansion of the dairy sector in the post milk quota era. A limited access to land for example will lead to greater intensification of dairy farms, which might consequently result in excess nutrient surplus going into the soil. To take full advantage of the abolition of the milk quota system especially in the Republic of Ireland, policy makers should therefore focus on increasing dairy farmers' access to land.

As noted earlier it is important to stress that some level of care is necessary in the interpretation of these results. Firstly, the model is a rather simple comparative static PMP model. In reality, farmers respond to changes in policy in a dynamic way. However, modelling the dynamic behaviour of the farmers will require additional technical-economic relationships and information that might be difficult to access. Also, in the model, farm gross margin was simultaneously optimised on the assumption of optimal allocation of dairy production inputs and outputs across farm types. However, the assumption of profit maximization may not always be the goal of all farmers (for example, other objectives may include minimization of labour use and ensuring minimal environmental impact in dairy production). It is nevertheless in line with economic theory which is necessary to predict economic behaviour of the different farm types. It should also be acknowledged that in the real world, access to land will not be as simple as has been assumed in this study and is in fact a real limitation to the expansion of the dairy sector. This is because access to land is usually influenced by other factors such as other agricultural activities and the quality of the accessible land available. Additionally, this study was based on representative farm types such that the effect of wide ranging heterogeneity that may exist between individual farms production characteristics are not fully considered.

In spite of the aforementioned limitations of this study, the results of the analyses using the PMP modelling approach contributes to the existing literature by providing empirical evidence on the economic and environmental effects of alternative environmental policy instruments in dairy farms. This will be useful in limiting excess nutrient surplus to the soil in the post milk quota era.

Further research in line with this study can be carried out to include other agricultural sectors such as the beef and arable sectors, which will provide empirical evidence of the impact of the policy changes on other agricultural sectors on the island of Ireland. Such studies could also include looking at the effects of adjustments in the use of production inputs or farming management practices such as reducing the amount of protein in concentrates or the transfer of surplus manure especially from the large dairy farms with higher manure nutrient inputs to the smaller farms where they can still be utilised.

Declaration of Competing Interest

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

Acknowledgments

This study is funded by Teagasc under the Walsh fellowship programme. The authors thank Agri-Food and Biosciences Institute, Northern Ireland for providing technical supports. We also thank the Department of Agriculture, Environment and Rural Affairs (DAERA), Policy and Economics Division, Northern Ireland for providing access to data. We appreciate the contribution of the anonymous reviewers in improving the paper.

Appendix A. Empirical specification of the PMP model

The empirical specifications of the model are presented in Eqs. (A1) to (A19).

A.1. First phase of the PMP model

$$aximize\ \Pi = \sum_{d}\sum_{k} X_d p_{dk} y_{dk} - \sum_{d}\sum_{i} X_d \omega_{di} p_i - \sum_{d}\sum_{n} F_{dn} p_n - \sum_{d} M_d h_d - \sum_{d} C_d j_d - \sum_{d} L_d v_d \quad (A1)$$

Where the indices d, k, I, and n represent sets
Π = the objective function value
X_d = vector of dairy activities d
p_{dk} = the price per unit for output k for dairy activity d
y_{dk} = the yield of output k for dairy activity d
ω_{di} = input i per unit of activity d
p_i = accounting costs per unit of input i,

F_{dn} = amount of chemical fertilizer n used

p_n = Price of chemica fertilizer n

M_d = volume of manure for each dairy activity d
h_d = price of spreading manure
C_d = volume of concentrates for each dairy activity
j_d = price of concentrates for each dairy activity
L_d = ha of extra land after milk quota is abolished
v_d = price of extra land for each dairy activity

Eq. (A1) is the linear objective function in which the variable costs are described as a linear function of prices and quantities. The first element on the right-hand side of equation represents the revenue from dairy production activities, that is, revenue from the sales of milk, and calves. The second element is the total variable costs excluding the costs of chemical fertilizer, the cost of spreading manure and the costs of concentrates. The third element is the cost of chemical fertilizer and the fourth element is the cost of spreading manure. The fifth element is the cost of concentrates, while the sixth element is the cost of renting extra land. Labour and capital are assumed not to be constraining factors in the model and farms can rent land up to a maximum of 20 ha at a cost. The 20 ha land size is chosen based on the historical data on land area rented by dairy farms in the study area.

The objective function is subject to the following inequality constraints

$$\sum_{d} \delta_{dl} X_d \leq \sum_{d} T_d\ [\lambda_l] \quad (A2)$$

$$T_d \leq B_d + L_d \quad (A3)$$

$$L_d \leq a \quad (A4)$$

The expression in Eq. (A2) represents the land constraint where δ_{dl} is the use of land per dairy activities in hectare per head. T_d is the total land available per dairy cow activity represented in Eq. (A3). L_d is the hectares of land rented while B_d is the initial land available per dairy cow activity and a in Eq. (A4) is the maximum amount of land that can be rented. The maximum amount of land that can be rented was obtained from the average of the historical data used for analysis. λ_l is the shadow price of land which represents the increase in the objective function if the land variable is made less restrictive. The shadow values resulting from the land constraint is comparable to the land rental values and are determined simultaneously with other parameters in the first phase of the model.

$$\sum_{d} \delta_{dq} X_d \leq b_q\ [\lambda_q] \quad (A5)$$

Eq. (A5) represents the dairy quota constraint where δ_{dq} is the dairy quota use per dairy cow activity. b_q represents the dairy quota availability while λ_q is the shadow price of milk quota. It should be emphasized that quota was not a constraint for Northern Ireland and as such was binding only for the Republic of Ireland model.

$$\phi_{dn} X_d - F_{dn} \leq 0 \quad (A6)$$

The expression in Eq. (A6) represents the chemical fertilizer application balance where ϕ_{dn} is the application of chemical fertilizer n per dairy cow activity in Kg per head.

$$\psi_d X_d - M_d \leq 0 \quad (A7)$$

The expression in Eq. (A7) represents the manure balance where ψ_d is the manure input in m^3 per dairy cow activity and M_d is the volume of manure from each dairy activity.

$$\gamma_n \psi_d X_d - A_{dn} \leq 0 \quad (A8)$$

The expression in Eq. (A8) is the manure nutrient balance where A_{dn} is the nutrient from manure variable in Kg and γ_n is the manure conversion ratio per dairy activity, in kg per m^3.

$$\sum_{d}\sum_{n} \gamma_n \psi_d X_d - \sum_{d}\sum_{n} \rho_{dn} X_d \leq 0 \quad (A9)$$

The expression in Eq. (A9) represents the constraints from the nitrate directive. In the model, derogation is allowed as N from manure cannot exceed 250 Kg N per hectare. The first expression is the nutrient from animal manure for each dairy production activity measured in Kg while the second expression represents the maximum allowable nutrient from manure. ρ_{dn} is the manure limit in Kg per head of dairy production activity.

$$\Theta_d X_d - C_d \leq 0 \quad (A10)$$

Eq. (A10) represents the concentrates balance where Θ_d is the concentrates per dairy livestock unit measured in terms of energy from concentrates in Feed Unit for Lactation (UFL) per head for each dairy production activity

$$\Omega_d X_d - E_d \le 0 \tag{A11}$$

The expression in Eq. (A11) represents the total energy balance where Ω_d is the total energy requirement per livestock unit measured in UFL per head for each dairy production activity. 1 kg dry matter of grass equals 1 unit of feed for lactation (UFL) (McCarthy et al., 2011). Subtracting the energy input from concentrates (C_d), from the total energy requirement (E_d) gives us the energy obtained from grass for each of the dairy production activities as presented in Eq. (A12). The estimated energy output from grass was found to be comparable to that estimated using the grass calculator for the Republic of Ireland (McCarthy et al., 2011).

$$E_d - C_d = G_d \tag{A12}$$

To estimate the nutrient output from grass, the energy from grass is converted to Kg dry matter and multiplied by appropriate coefficients (ξ_n) measured in kg per kg DM. G_d is the nutrient output from grass measured in unit of feed for lactation (UFL) (Eq. (A13)).

$$\xi_n G_d = N_{dn} \tag{A13}$$

N_{dn} is the nutrient output from grass measured in Kg.

$$A_{dn} + F_{dn} - N_{dn} = S_{dn} \tag{A14}$$

The nutrient surplus per dairy production activity S_{dn} is obtained from expression (A14) by subtracting the total nutrient input from chemical fertilizer and manure from the nutrient output from grass

$$X_d \le X_d^* + \varepsilon\ [\lambda_d] \tag{A15}$$

Eq. (A15) is the calibration constraint and it forces the program to reproduce base year observed activity levels by putting upper limits on activity levels based on activity levels in the base period (Helming et al., 2001). This is undertaken following Howitt (1995), by including a perturbation (ε, is a very small number) to decouple the resource and calibration constraints. In the equation, λ_d represents the shadow values of the calibration constraint.

$$X_d,\ F_{dn},\ A_{dn},\ M_d,\ C_d G_d,\ E_d > 0 \tag{A16}$$

The expression in Eq. (A16) is the non-negativity constraint which ensures that no negative activity level is observed.

A.2. Second phase of the PMP

In the second stage of the PMP model, the shadow values of the calibration constraints are used to construct non-linear variable cost functions excluding costs of chemical fertilizer, cost of concentrates and cost of spreading manure. To overcome the problem of underdetermination of the parameters (loss of degree of freedom) of the PMP methodology, in this study, prior information about supply elasticities has been adopted to calculate the parameters of the dairy model costs functions for Northern Ireland and the Republic of Ireland. An approximate price elasticity estimate of 1 obtained from Kostov (2008) was used in the analysis based on the fact that dairy production activities are expected to become more commercially orientated and price responsive in the post milk quota abolition era. The shadow values from the first stage calibration constraints are combined with the average production costs to calibrate the quadratic costs function in the model. The slope of the marginal costs curve for the dairy production activities is presented in Eq. (A17)

$$\beta_{di} = \frac{\lambda_d + \omega_{di} p_i}{\eta_d X_d^*} \tag{A17}$$

The intercept coefficient of the marginal costs function (α_d) is specified in Eq. (A18) as

$$\alpha_{di} = \frac{(\lambda_d + \omega_{di} p_i).\ (\eta_d - 1)}{\eta_d} \tag{A18}$$

Where η_d equals *a priori* supply elasticity of dairy production activity.

A.3. Third phase of the PMP

In the third phase of the PMP, the linear cost expressions in Eq. (A1) (second element in the equation) is replaced by the quadratic costs functions (Eq. (A19)) using Eqs. (A17) and (A18). The calibration constraints in the first phase (Eq. (A15)) are removed. In addition, a new element to analyse effect of the application of an envisaged nutrient surplus tax policy is also included.

$$ax\ \Pi = \sum_d \sum_k X_d p_{dk} y_{dk} - \sum_d \sum_i (\alpha_{di} + 0.5\beta_{di} X_d) X_d - \sum_d \sum_n F_{dn} p_n - \sum_d M_d h_d - \sum_d C_d j_d - \sum_d L_d v_d - \sum_d Z_d r_d \tag{A19}$$

Where Z_d is the N surplus above threshold for which the farmer is taxed, r_d is the levy on N surplus in monetary unit per Kg. The model was written in GAMS programming language and was solved using the non-linear solver CONOPT3. The methodology involved setting alternative policy scenarios with a base scenario that is used as a reference point for counterfactual analysis. For the purpose of allowing for independent simulations based on the decision-making behaviour of the dairy farmers in each country and clusters, each, country has been modelled separately. An HMRC Exchange rate of £1 to €1.178 was used in converting Northern Ireland's Pounds (£) to euros (€)HMRC, 2017.

Appendix B. Model justification

The initial analysis for this study was undertaken prior to milk quota abolition in 2015. In order to validate the model, we compared the model results with actual data for the year 2016 post milk quota abolition using data obtained from the Teagasc National Farm Survey (NFS, Republic of Ireland) and the Northern Ireland Farm Business Survey (FBS, Northern Ireland). We used the methodology described in Section 2.1 to conduct a cluster analysis for a sample of 314 and 101 dairy farms for the Republic of Ireland and Northern Ireland respectively. The box plots in Figs. B1 to B3 shows the distributions of all the clusters. The same variables of milk yield, herd size and utilised agricultural area were used for the cluster analysis. The results show that the clusters are comparable to the clusters used for the model analysis.

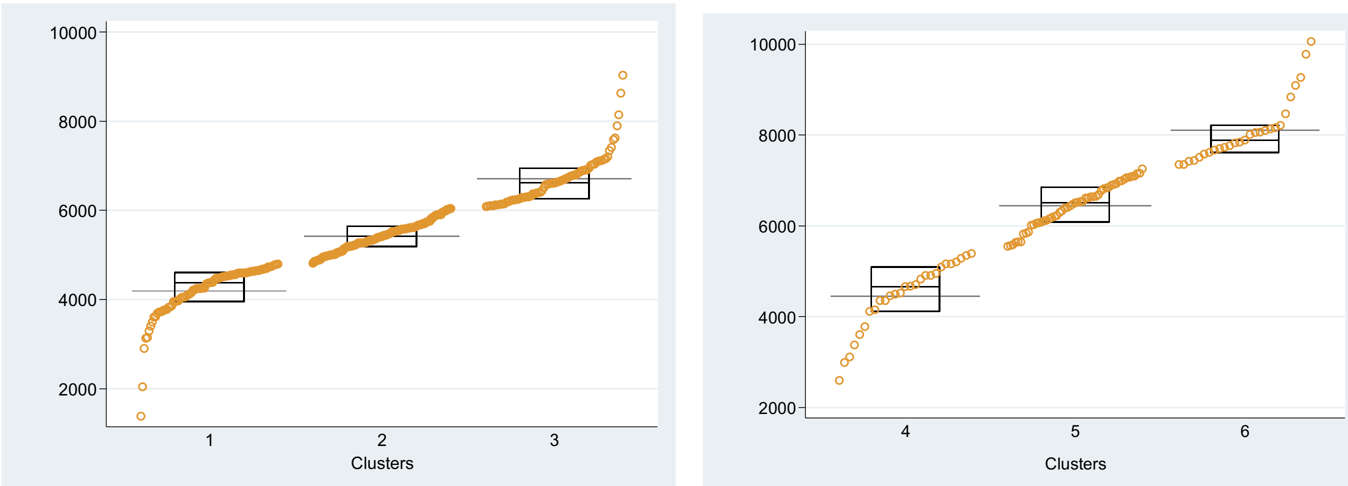

Fig. B1. Box plots showing the distribution clusters in respect of the milk yield variable (2016).

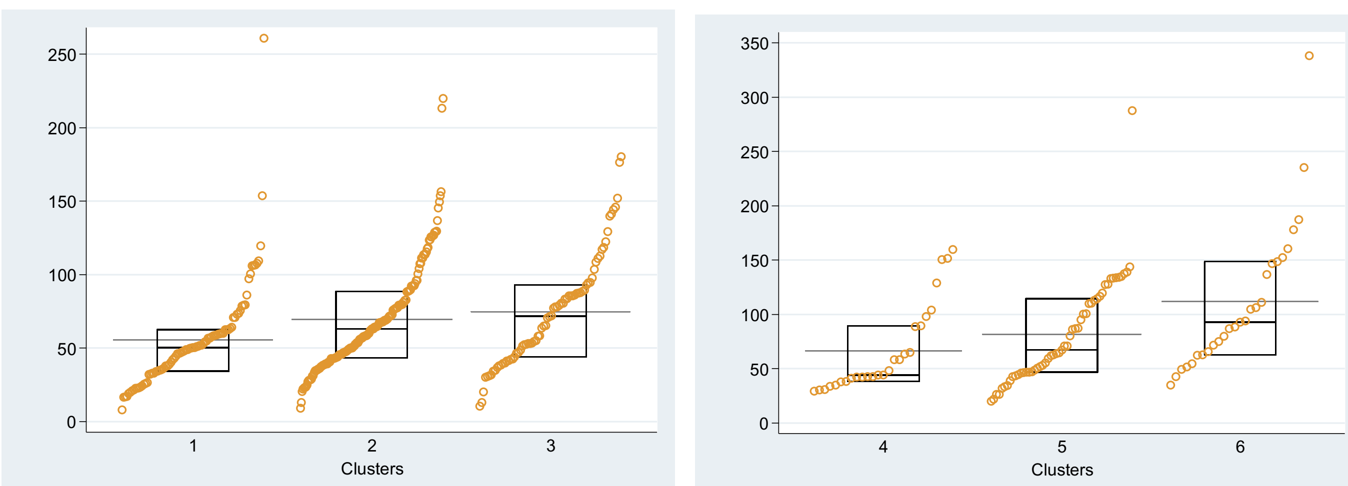

Fig. B2. Box plots showing the distribution clusters in respect of the UAA variable (2016).

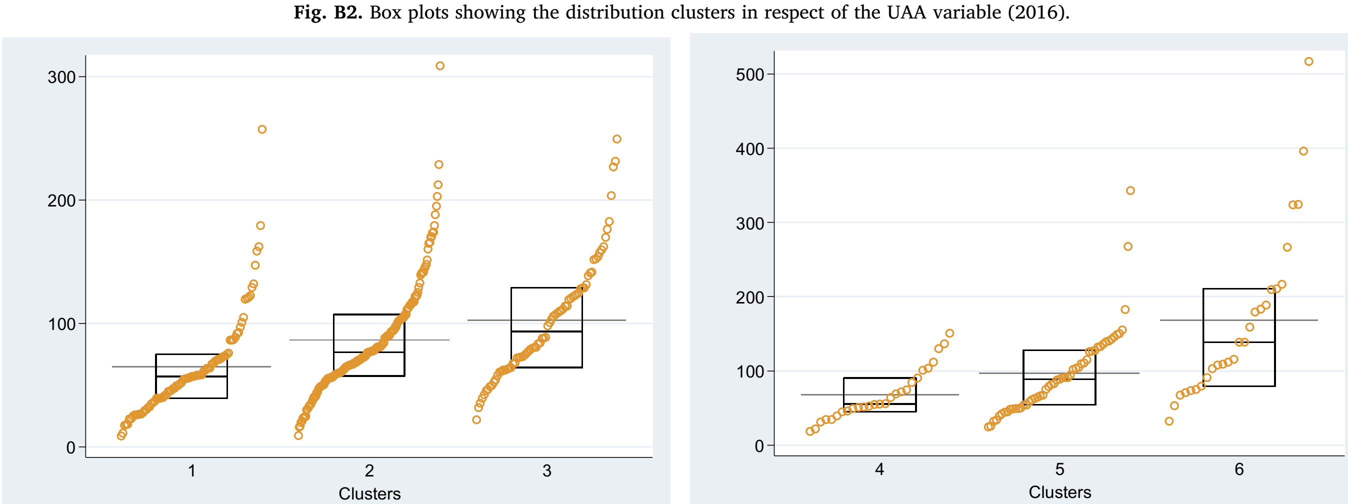

Fig. B3. Box plots showing the distribution clusters in respect of the herd size variable (2016).

We estimated the N balance using the methodology described in Section 2.3 on the 2016 data and compared the results to the model results. The results of the analyses are presented in Tables B1 and B2. A graphical representation of the results is also provided in Figs. B4 to B6. The analysis showed that to a large extent, our model correctly predicted the effect of the abolition of the milk quota system on herd size, gross margin and N balance. For example, just as the model results, the actual data for 2016 showed an increase in herd size for all clusters in the Republic of Ireland (clusters 1, 2 and 3) whereas, it remains relatively the same for Northern Ireland (clusters 4, 5 and 6). A 2016 HMRC Exchange rate of £1 to €1.3 was used in converting Northern Ireland's Pounds (£) to euros (€).

Table B1
Comparison of model results for S1 scenario to actual 2016 data for clusters 1, 2 and 3.

Variables	Cluster 1			Cluster 2			Cluster 3		
	Base (N = 31)	Model	2016 (N = 85)	Base (N = 57)	Model	2016 (N = 155)	Base (N = 24)	Model	2016 (N = 74)
Herd size	53.4	70.1	64.93	63.4	84.2	86.61	92.6	131.3	102.75
Stocking density (cow/ha)	1.22	1.10	1.22	1.22	1.17	1.29	1.31	1.45	1.47
Gross margin (€)	30,638	31,716	43,904	52,326	62,650	79,514	94,195	122,224	109,432
N surplus (Kg/ha)	98.2	88.6	96.1	141.5	135.9	165.15	207.28	229.68	215.41

Table B2
Comparison of model results for S1 scenario to actual 2016 data for clusters 4, 5 and 6.

Variables	Cluster 4			Cluster 5			Cluster 6		
	Base (N = 24)	Model (S1)	2016 (N = 23)	Base (N = 36)	Model (S1)	2016 (N = 51)	Base (N = 14)	Model (S1)	2016 (N = 27)
Herd size	64.5	64.5	68.6	95.0	95.0	96.42	183.9	183.9	168.22
Stocking density (cow/ha)	1.05	1.05	1.03	1.28	1.28	1.20	1.60	1.60	1.50
Gross margin (€)	46,654	46,654	37,099	92,966	92,966	92,412	199,414	199,414	216,251
N surplus (Kg/ha)	132.2	132.2	113.91	161.5	161.5	153.82	239.39	239.39	246.42

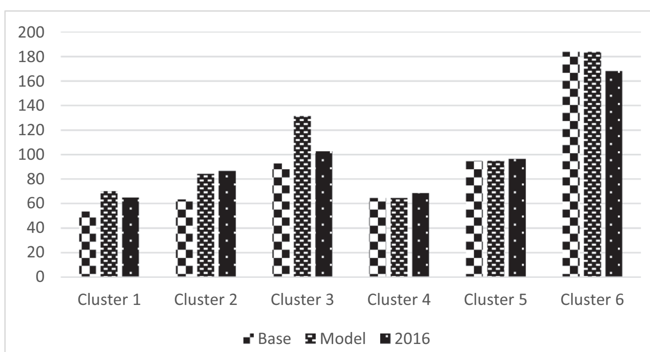

Fig. B4. Comparison of model herd size to actual 2016 data for S1 scenario analysis.

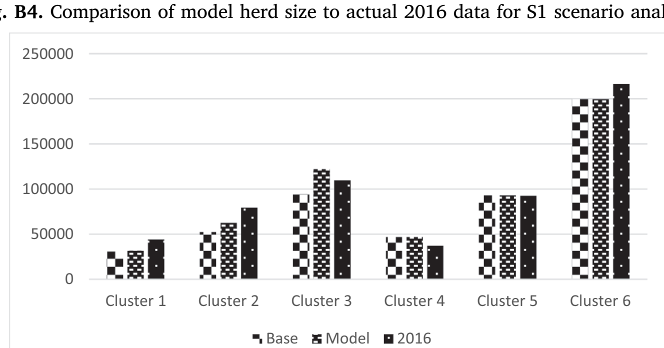

Fig. B5. Comparison of model gross margin (€) to actual 2016 data for S1 scenario analysis.

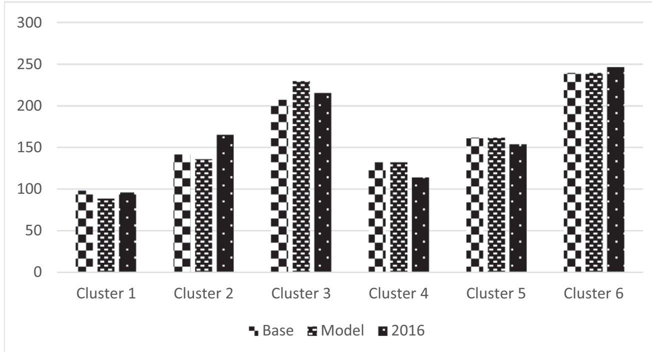

Fig. B6. Comparison of N balance (Kg/ha) to actual 2016 data for S1 scenario analysis.

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