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Empirical evidence on mitigation and co-benefit potential on dairy and sheep-beef farms with currently used farm practices

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Table of Contents

Table of Figures

1 Introduction

The agricultural sector in New Zealand is a major source of both nutrient leaching (nitrogen (N) and phosphorus (P)) and greenhouse gas (GHG) emissions. The amount of N leached from agricultural activities, according to Environment Aotearoa 2015, increased by 28.6% over the 1990–2012 period (Ministry for the Environment and Statistics New Zealand 2015). During the same time, agricultural GHG emissions contributed approximately 48 percent of New Zealand's total emissions (Ministry of the Environment 2015).

The New Zealand government released in 2014 the National Policy Statement for Freshwater Management, largely aiming at controlling nutrient leaching across the country. What effects will this reform be likely to have on greenhouse gases? This report is part of a study (Daigneault et al. 2016) to estimate this. Our results will help to validate nutrient abatement cost curves used in a national model NZFARM.

Mitigation of agricultural GHGs plays a critical role in climate mitigation (McCarl & Schneider 2001; Maraseni 2009). Research has also found that in the United States change in agricultural activities can have significant benefits for both GHG mitigation and water quality (e.g. Pattanayak et al. 2005; Boehlert et al. 2015). For example, improved efficiency of nitrogen usage in fertilisers or manure management can reduce the emissions of nitrous oxide (N_2O) via the nitrification process while controlling nitrogen loss into rivers and lakes through surface runoff or groundwater. Faeth and Greenhalgh (2000, 2002) have explored how water quality and GHG policy could interact. Early New Zealand work on this issue includes Kerr and Kennedy (2009), Daigneault et al. (2012), Yeo et al. (2014), Coleman and Yeo (2014), and Kerr (2013).

In this report, we use historical data to estimate dairy and sheep/beef farmers' nitrogen and phosphorus management efforts. That is, the amount of nutrient leached or lost per unit of output (or stock unit) after controlling for factors that affect nutrient leaching and loss but that are outside the farmer's control (e.g. climate, soil, slope). Since nutrient leaching is a function of the interaction of many variables, a generalised version of a Cobb-Douglas function is used. Farmers' nutrient management efforts are estimated as the residuals from a multivariate regression. For dairy farms, consistent with the Cobb-Douglas function, we use a logarithmic specification. We assume that when nutrients are regulated through the Freshwater Reforms farmers' practices will tend to become more like what the currently efficient farmers are doing. Thus we use the nutrient management effort measure as a proxy for the pressure that will be imposed by the Freshwater Reform.

Having established a proxy for effort to reduce nutrients, we estimate how much agricultural GHGs might be mitigated if all farmers face pressure to change practices to reduce nutrient leaching. We find modest co-benefits from control of nitrogen leaching for reductions in greenhouse gases through changes to reduce nitrogen leaching per unit of product produced within current farm management practices. A 1% reduction in nitrogen leaching leads to around a quarter of a percent reduction in nitrous oxide and a tiny reduction in methane. Our 'ambitious' scenario suggests that dairy (sheep/beef) farmers might reduce nitrogen leaching by 23.5% (12%) and total greenhouse gases by 2.6% (1.2%) without changing production levels.

The rest of this report proceeds as follows. In Section 2, we discuss the conceptual logic behind our modelling approach. We describe our data and present our empirical strategy in Section 3. Section 4 shows the results and Section 5 concludes.

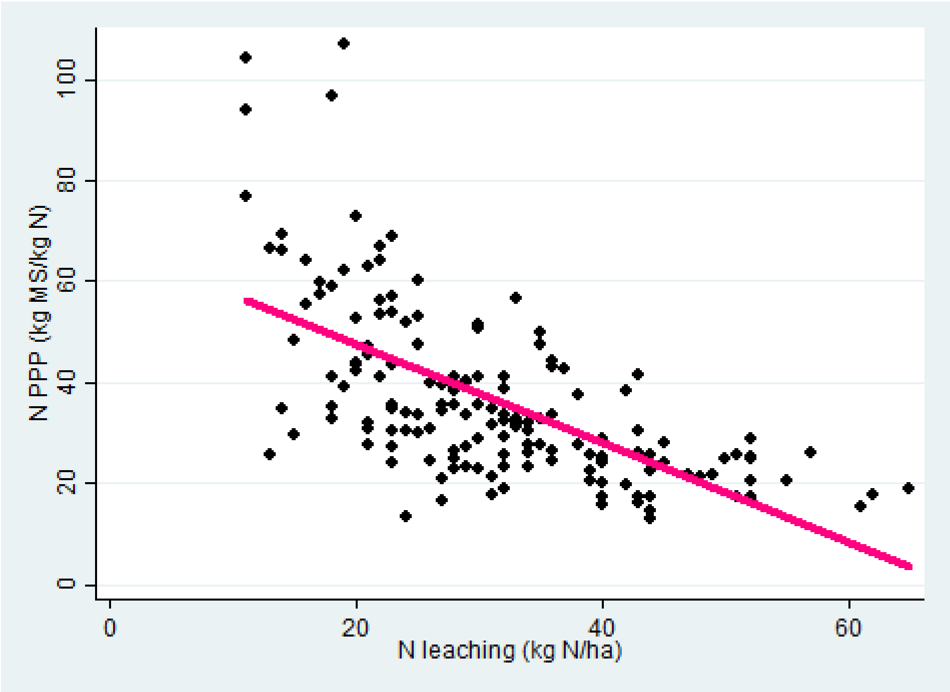
2 Conceptual approach

When farmers face pressure to reduce nitrogen leaching and phosphorus loss as part of efforts to improve freshwater quality, they will need to change their farm practices. Those changes in behaviour will have implications for greenhouse gas emissions. Others have modelled behaviour changes that they think are likely using simulation models (Ridler et al. 2010; Doole et al. 2012; Daigneault et al. 2012). We take a different approach. We assume that when farmers face pressure to reduce nutrients they will tend to behave more like those who are already running nutrient efficient farms and use data from actual farms and farmer decisions to predict those shifts in behaviour and their implications.

This seems plausible but is only an assumption. We do not know why the farmers in our sample are behaving differently without regulation and therefore cannot confidently predict the effect regulation will have on those behavioural differences. We are using statistical relationships but not identifying a caussal model. Implicitly, we are assuming that the more nutrient efficient farmers are actively trying to reduce nutrients. This could be because they feel a sense of personal responsibility for water ways or because they experience some social pressure. If this is true, their responses may be similar to those they and others would make when faced with regulatory pressure.

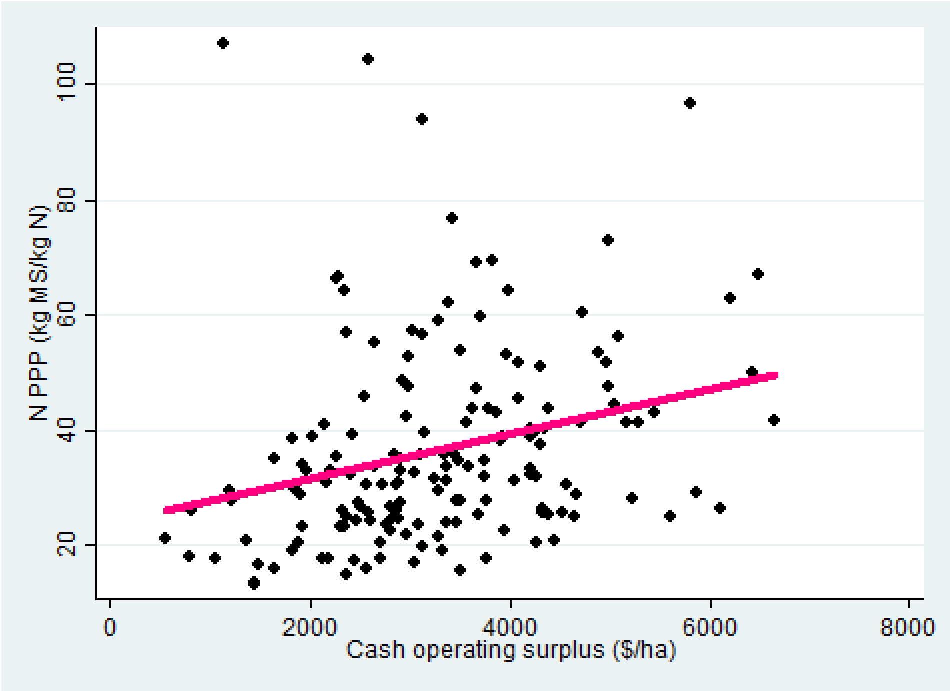
An alternative plausible explanation is that high levels of production per unit of nutrient leaching are associated with higher profitability and what we are observing is differences in farmers' capability to maximise profit. Previous research (Anastasiadis & Kerr 2013) found that, dairy farmers who produced more milk solids per unit of N leached (Product per unit N pollution, N PPP) also leached less in total in 2008 (Fig. E1) while having higher operating surplus in 2010 (Fig. E2). This supports the alternative hypothesis that actions to improve production per unit of N leaching might be motivated by improved profitability instead of, or as well as, improved environmental performance. We cannot distinguish these motivations, and results should be interpreted with this caveat. Our simulation results would hence provide an upper bound on the level of response that might be expected.

Figure 1: N leaching and production per unit of N leached – Dairy farms: 2008



Source: (Anastasiadis & Kerr 2013) figure 21

Figure 2: Production per unit of N leaching and cash operating surplus – Dairy farms, 2010



Source: (Anastasiadis & Kerr 2013) figure 28

To model the effect of freshwater reforms we first try to identify farmers who are running nutrient efficient farms. We want to separate the farms that have geophysical characteristics that make their nutrient leaching lower from the farmer actions that affect leaching. Thus, we control for observable geophysical variables and identify farms that still have surprising low nutrient loss.

Second, we estimate the extent to which these same farms also have surprisingly low greenhouse gases. We then run scenarios to explore how changes in nutrient leaching behaviour could affect greenhouse gases in the sample as a whole. For our scenarios, we consider three levels of farmer response; responses will vary with the intensity of the freshwater regulation and with the extent to which the variation we identify is driven by effort rather than capability.

3 Data

We use unit record annual farm level data collected as part of the Ministry of Agriculture and Forestry (MAF) monitor farm reporting, from 2008 to 2010 (Ministry of Agriculture and Forestry, dataset, 2010).[1] MAF combined these data by region and farm type to construct representative model farms, which were the focus of their monitor farm reports (e.g. Ministry of Agriculture and Forestry 2011). The farms in the dataset are not randomly selected, but are chosen in an attempt to create a representative sample.[2]

Estimates of *Nitrogen leaching* (kg N/ha), *Phosphorus loss* (kg P/ha) and *GHG emissions* (methane, nitrous oxide and total: T CO2-eq/ha) for the farms in the dataset were calculated from reported farm characteristics and management practices using the OVERSEER© (version 6.2.1) developed by AgResearch. The original OVERSEER files were run through this more recent version of OVERSEER by AgResearch to be more consistent with current scientific understanding and other recent modelling. Some of the inputs have been set to default values because they were not used in earlier OVERSEER versions and hence were not part of our data. The use of a model means that some variability in N leaching and greenhouse gas emissions is not captured.

Our dataset is an unbalanced panel of 384 dairy farms and 404 sheep/beef farms over four years.[3] Out of 384 dairy farm observations, 150 farms were observed in only 1 year, 41 farms were observed in 2 years, 23 farms were observed in 3 years, and 18 farms were observed in all 4 years. The number of dairy farm observations in each year also varied: 138 farms were observed in 2008, 63 observed in 2009, 86 observed in 2010, and 97 observed in 2011. Among the total 404 sheep/beef farm observations, 141 farms were observed in 1 year, 44 in 2 years, 57 in 3 years, and only 1 in 4 years. In the sheep/beef panel, 103 farms were observed in 2008, 94 observed in 2009, 103 observed in 2010, and 104 observed in 2011.

The dairy farms are well distributed across regions: 2.9% of our observations in Bay of Islands; 18.2% in Canterbury; 2.3% in the Central Plateau; 7.8% in the East Coast of North

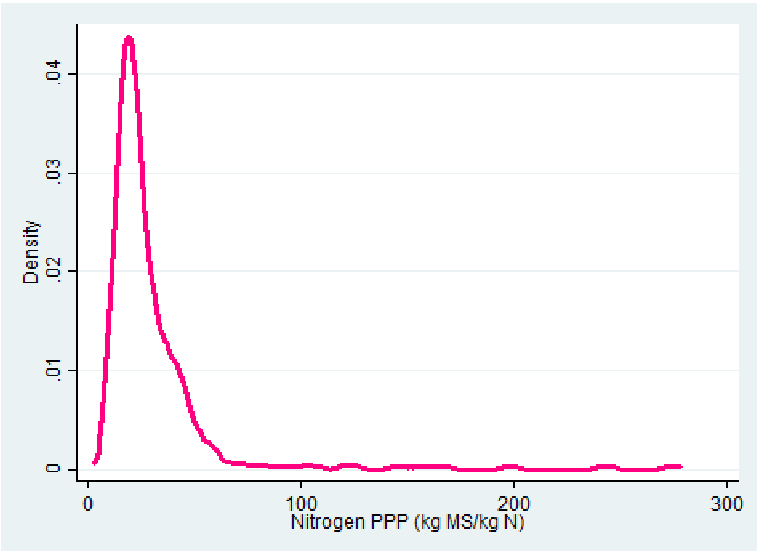
1 MAF is now part of the Ministry of Primary Industries.
2 These farms may on average be run more efficiently than the true population, simply on the basis that they agreed to participate in this programme. Farms in the lower 'tail' of the productivity distribution are unlikely to be included.
3 Deer farms are included in the sheep/beef category.

Island; 0.5% in King Country/Taihape; 8.3% in Manawatū/Wanganui; 7.0% in Northland; 1.0% in Otago; 17.7% in Southland; 14.8% in Taranaki; 19.0% in Waikato/Coromandel; and 0.3% in Wellington. Our sheep/beef farm observations are also widely distributed: 2.5% in Auckland; 1.2% in Bay of Islands; 11.6% in Canterbury; 3.2% in the Central Plateau; 20.8% in the East Coast of North Island; 5.2% in the South Island High Country; 4.2% in King Country/Taihape; 7.3% in Manawatū/Wanganui; 2.5% in Marlborough; 8.4% in Northland;13.4% in Otago; 14.6% in Southland; 0.5% in Taranaki; and 4.5% in Waikato/Coromandel.

For each farm in each year we observe *Total effective area*. For dairy farms we observe the area used for milking and grazing the dairy herd (ha), and *Milk solids*, total milk solid production for the farm (kg MS). For sheep/beef farms we observe separate stocking rates for sheep, beef and deer. We use *revised stock units* as defined by (Nicol and Brookes 2007).[4]

Figure 3, Figure 4 and Figure 5 give the distributions for product per unit N, P and GHG pollution (PPP hereafter) on dairy farms. They have been constructed such that the more efficient farms are to the right and the less efficient farms are to the left. For both figures, we observe a skewed distribution with a large number of relatively less efficient farms and a long tail of farms that are more efficient.[5]

Figure 3: Distribution of Nitrogen PPP on dairy farms.



4 The original stock units were defined by (Coop 1965).
5 It seems likely that some of the farm observations in the tail of the Nitrogen and GHG PPP distributions may involve either data error or extremely unusual circumstances. Their existence does not affect our results.

Figure 4: Distribution of Phosphorus PPP on dairy farms.

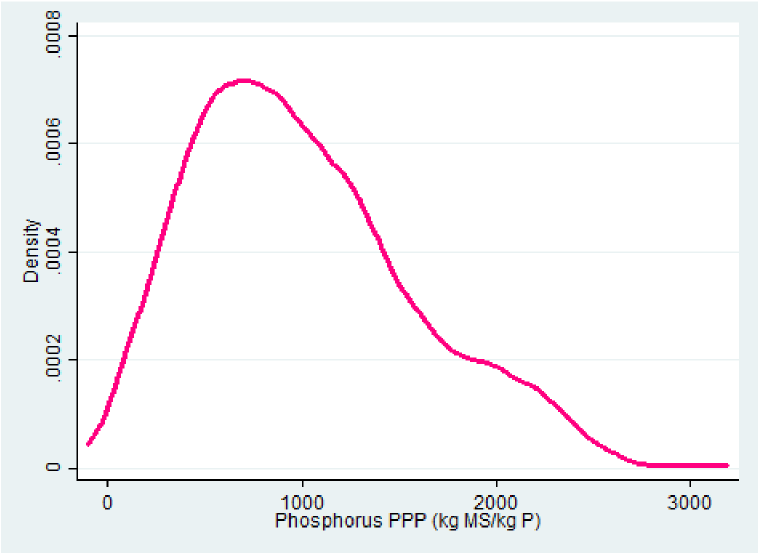
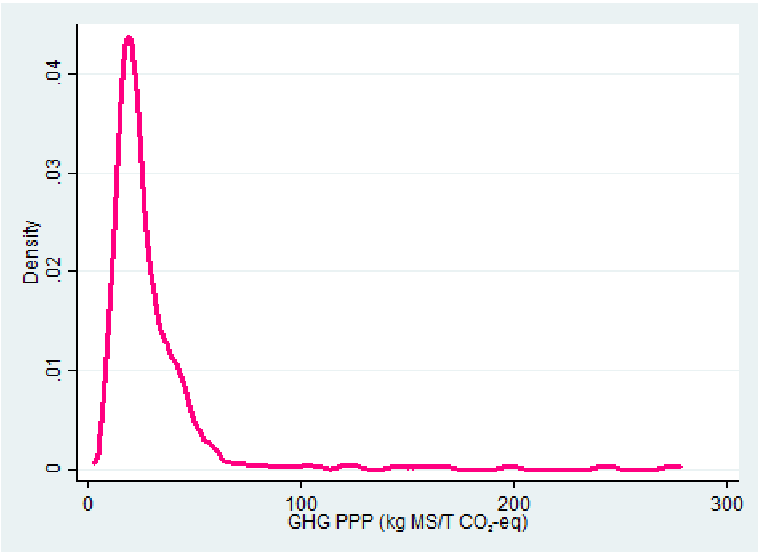


Figure 5: Distribution of GHG PPP on dairy farms.



There is significant variation in PPP among dairy farms. The most N efficient farms produce more than twice the amount of milk solids per kg N relative to the farms with median N efficiency. The most GHG efficient dairy farms produce 25% more milk solids per T GHG than the least efficient dairy farms. Results for sheep/beef farms are similar (though the GHG variation is even greater). The distributions are given in the Appendix.

How much of this variation in N leaching is due to factors that can be managed on existing farms and could respond to regulation as a part of the Freshwater reforms is our first question. How those regulation-driven responses could affect the distribution of GHG PPP is our second question.

We now describe the farm characteristics included in the monitor farm data that are used for our analysis. We group the farm characteristics into two categories: exogenous characteristics of the land and farming practices. Some descriptive statistics are reported in Tables E1 and E2.

Table 1: Summary table of variables: Dairy farms

Variable	Mean	Std. Dev.	Min	Median	Max
Rainfall (mm)	1162.4	386.0	425.0	1200.0	3000.0
Temperature (°C)	13.0	1.7	8.1	13.0	18.0
Total effective area (ha)	166.0	88.8	40.0	145.0	527.0
Production (T MS)	179.9	115.0	29.6	148.0	815.8
N leaching (kg N/ha)	48.4	24.4	6.0	44.5	160.0
P loss (kg P/ha)	1.5	1.3	0.3	1.2	9.8
GHG emissions (T CO_2-eq/ha)	12.2	3.2	3.4	12.0	22.3
Methane (T CO_2-eq/ha)	7.6	1.8	2.0	7.5	12.7
Nitrous oxide (T CO_2-eq/ha)	2.9	1.0	1.0	2.8	6.2
N PPP (kg MS/kg N)	29.4	26.9	5.7	22.0	274.5
P PPP (kg MS/kg P)	1003.8	565.7	54.2	926.5	3037.5
GHG PPP (kg MS/T CO_2-eq)	89.8	19.0	30.6	87.4	225.4
Stocking rate (cows/ha)	2.8	0.7	0.9	2.8	4.9
Production per animal (MS/cow)	364.7	63.3	171.4	363.0	763.6

Table 2: Summary table of variables: Sheep and beef farms

Variable	Mean	Std. Dev.	Min	Median	Max
Rainfall (mm)	1131.5	355.8	373.6	1100.0	2000.0
Temperature (°C)	12.0	2.2	7.0	12.0	17.0
Total effective area (ha)	1161.3	2332.3	58.0	493.0	21910.0
N leaching (kg N/ha)	12.4	7.0	2.0	12.0	40.0
P loss (kg P/ha)	0.9	1.0	0.0	0.6	6.7
GHG emissions (T CO_2-eq/ha)	3.7	1.7	0.2	3.7	14.1
Methane (T CO_2-eq/ha)	2.7	1.3	0.1	2.7	10.7
Nitrous oxide (T CO_2-eq/ha)	0.8	0.4	0.1	0.8	3.1
Revised stock unit: sheep (sheep/ha)	5.5	4.1	0.0	4.9	24.5
Revised stock unit: beef (beef/ha)	2.9	3.1	0.0	2.3	25.6
Revised stock unit: deer (deer/ha)	0.9	3.2	0.0	0.0	21.6

Some characteristics are out of the control of an existing farm. We observe mean annual *Rainfall* (mm); mean annual *Temperature* (°C); *Topography*, classified as flat land (80.2% for dairy and 54.0% for sheep/beef),[6] and non-flat hill (19.8% and 46%); and *Soil group*, classified as peat (1.3% and 0.3%), podzol (2.6% and 0.0%), pumice (3.1% and 6.9%), recent yellow-grey earth (YGE) (15.1% and 23.0%), sands (2.9% and 1.7%), sedimentary (46.6% and 58.2%) and volcanic soil (30% and 9.9%).[7] We create a binary variable, *South Island*.

Other characteristics are within the control of an existing farm. For both dairy and sheep/beef farms we include measures of output (*milksolids* and *stocking rate*[8]) because our focus is on reductions in pollution per unit of output. Farmers do have control over the intensity of their production per hectare and reducing production intensity is one potential mitigation option. Stocking rate is a coarse measure of production but no other measure is available in our data. Previous work has found that sheep-beef stocking rates are strongly driven by geophysical characteristics at least at a high level of aggregation (Figure 2.1 in Timar and Kerr 2014) so farmers' key decision may be whether to keep land in pasture.

Other characteristics are included as controls for activity and hence pollutants that have been moved from one farm to another during the year, for infrastructure that is unlikely to be changed (e.g. irrigation) and for a specific mitigation (DCD) which is not currently available. The movement of activity does not constitute on-farm mitigation although for freshwater, if activity is moved outside of the catchments of greatest concern it may still have value. For dairy farms, we observe; *Dairy replacements*, the number of replacement heifers per hectare; *Cows wintered off*, the number of animals wintered off per hectare; *Irrigated*, showing whether a farm is irrigated; and *DCD used*, the application of nitrification inhibitor DCD.

3.1 Empirical Strategy: the two-step model

We introduce first in this section a two-step regression model for dairy farms. The first (or step-one) regression equation takes the following form:

$$n_{it} = \alpha_0 + \alpha_1 m_{it} + \alpha_2 c'_{it} + \alpha_3 p'_{it} + \varepsilon_{it}. \quad (1)$$

The subscript i indexes the individual farm and t the year. The dependent variable n_{it} is the logarithmic scale of N leaching (or P loss) of farm i during year t. The independent variable m_{it} is the amount of milk solids produced in logarithm; c_{it} is a vector of variables that describe the controls for stock movement; and p_{it} is a vector of geophysical variables. All logarithmically transformed variables are mutually interactive. However, since some variables are binary we

6 For each of the following variables, the first percentage is for dairy farms and the second for sheep/beef farms.
7 These are the soil types available in the OVERSEER datafiles we have. AgResearch staff confirmed that these are the best we can use for this project.
8 We combine sheep, beef and deer stock units. The type of stock is within the farmer's control. Implicitly we are treating the output from farming different ruminants as socially equivalent.

could not take logarithms, for the dairy farms we include interactions of some key variables with production levels. The error term ϵ_{it} in Equation (1) is associated with the nutrient management effort (in logarithmic scale) that stems from the farmer's set of management practices but also reflects all other unexplained variability. It is adjusted by the shift parameter α_0 to have a zero mean.

For readers familiar with the theory of productivity growth, this regression specification can be viewed as coming from a Cobb-Douglas-type function, where nutrient leaching is "produced" by the interactions among all the "input" variables.[9] The error term coupled with α_0 is an analogue of the Solow residual.[10] Therefore, we extract the residual $\hat{\varepsilon}_{it}$ and define $\hat{\epsilon}_{it} = -\hat{\varepsilon}_{it}$ as a proxy for the total nutrient management effort for each monitored farm in a given year. Any increase in the value of this proxy is assumed to reflect an increase in effort to control nutrients.

The second (or step-two) regression equation explores how much GHGs can be potentially mitigated if farmers increase their nutrient management effort, controlling for other non-management variables listed in Equation (1):

$$g_{it} = \beta_0 + \beta_1 m_{it} + \beta_2 c'_{it} + \beta_3 p'_{it} + \gamma\hat{\epsilon}_{it} + \mu_{it}. \quad (2)$$

Throughout this report, we only concentrate on nutrient management effort on the main contributing GHGs from pastoral farming; that is, the GHG measure is the sum of emissions of methane and nitrous oxide.

The two-step model for sheep/beef farms follows the same structure discussed above but is with m_{it} replaced by a quadratic function of stock unit and without taking logarithms of n_{it} and g_{it}.

4 Results

Here we present the results for nitrogen in some detail. Similar analysis for Phosphorus loss is given in the Appendix

4.1 Estimates of N management effort

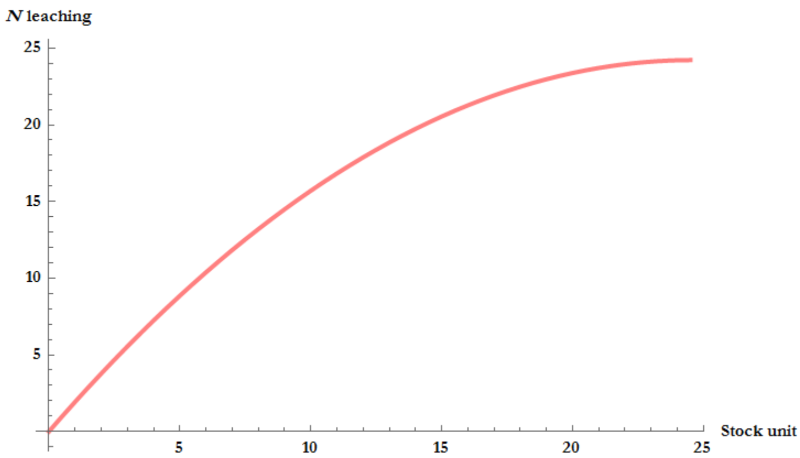
Tables E3 and E4 show a set of core results of the two-step regression approach. In the step-one regression for dairy farms all coefficients are consistent with expectations except rainfall, which is expected to have a positive effect on nitrogen leaching. Farms that produce more milk solids or carry more replacement heifers per hectare leach more. Farms in the South Island generally

9 Here we sacrifice the "meaningfulness" of unit (or dimension) to derive a specification from the Cobb-Douglas-type production function, in which the product is a product of all the input variables.
10 Any interested reader is referred to Chapter 10 of Barro and Sala-i-Martin (2004).

have relatively newer equipment; this may be why they leach less. Utilising nitrification inhibitors (DCDs) does lower leaching.[11]

In the step-one regression for sheep/beef farms, N leaching is associated with a concave function of stock unit per hectare controlling for all other variables (see Fig. 6).[12] It says that a farm having more stock units leaches more but at a decreasing rate.

Figure 6: Concave function of stock units per hectare.



4.2 Negative impact on GHGs of N management effort

We find that the impact of N management effort on GHG emissions is negative and highly significant for dairy farms. In other words, any incentive that stimulates more effort in nutrient control is likely to have the expected negative effect on GHG emissions, especially on nitrous oxide. The N management effort effect is still negative for sheep/beef farms but is insignificant for methane. The R^2 in our step 2 sheep/beef farms is suspiciously high, which makes us suspect that the algorithm used to calculate methane and nitrous oxide is not very sensitive to farm characteristics other than stocking rates. This leaves little room for the influence of management effort. This may reflect a lack of mitigation options without changing stocking rates on sheep/beef land.

11 DCDs are not currently used in New Zealand.
12 Stock unit per hectare is less than 24.58, the maximum for the concave function, for all sheep/beef observations except one farm, which has stock unit/ha 39.01.

Table 3: Regression results for dairy farms using the two-step model

	Step 1	Step 2		
	log(N leaching)	log(GHG)	log(CH_4)	log(N_2O)
log(milk solids)	0.675*** (0.0981)	0.727*** (0.0258)	0.728*** (0.0280)	0.726*** (0.0345)
log(rainfall)	−0.298* (0.129)	−0.0602 (0.0338)	−0.0632 (0.0367)	−0.0732 (0.0452)
log(temperature)	−0.0736 (0.268)	−0.0511 (0.0703)	−0.0132 (0.0763)	−0.140 (0.0941)
topography = non-flat hill	−0.0856 (0.0669)	0.000766 (0.0176)	0.00111 (0.0191)	−0.00324 (0.0235)
soil = peat	0.177 (0.228)	0.0629 (0.0600)	0.0619 (0.0651)	0.0568 (0.0803)
soil = podzol	0.125 (0.167)	0.0773 (0.0438)	0.0863 (0.0476)	0.0496 (0.0587)
soil = pumice	0.168 (0.153)	0.0780 (0.0403)	0.0825 (0.0437)	0.0747 (0.0539)
soil = recent YGE	0.0749 (0.0809)	0.0560** (0.0212)	0.0498* (0.0231)	0.0778** (0.0284)
soil = sands	0.131 (0.156)	0.0805* (0.0409)	0.0342 (0.0444)	0.174** (0.0547)
soil = volcanic	-0.0248 (0.0711)	0.0719*** (0.0187)	0.0754*** (0.0203)	0.0660** (0.0250)
log(cows wintered off)	−0.0238 (0.0127)	−0.0109** (0.00334)	−0.00805* (0.00362)	−0.0174*** (0.00447)
log(dairy replacements)	0.0831** (0.0299)	0.0731*** (0.00786)	0.0770*** (0.00853)	0.0677*** (0.0105)
year = 2009-10	−0.00514 (0.0761)	−0.0119 (0.0200)	−0.0126 (0.0217)	−0.0127 (0.0268)
year = 2010-11	−0.0600 (0.0689)	−0.0491** (0.0181)	−0.0486* (0.0197)	−0.0469 (0.0242)
year = 2011-12	-0.135* (0.0675)	−0.0581** (0.0177)	−0.0489* (0.0193)	−0.0813*** (0.0238)
south island	−0.293*** (0.0801)	−0.0333 (0.0210)	−0.0410 (0.0228)	−0.0236 (0.0282)
DCD used	−0.327** (0.0999)	−0.0957*** (0.0268)	−0.0267 (0.0291)	−0.302*** (0.0361)
irrigated	−0.0273 (0.104)	0.0560* (0.0273)	0.00464 (0.0297)	0.178*** (0.0366)
N residual		−0.111*** (0.0137)	−0.0516*** (0.0149)	−0.266*** (0.0184)
constant	6.175*** (0.927)	9.776*** (0.244)	9.395*** (0.264)	8.753*** (0.326)
No. observations	384	384	384	384
R-squared	0.215	0.780	0.730	0.756
adjusted R-squared	0.176	0.768	0.716	0.743

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. Here GHG = methane + nitrous oxide, measured in T CO_2-equivalent. Controls: topography = flat, soil = sedimentary.

Table 4: Regression results for sheep/beef farms using the two-step model

	Step 1	Step 2		
	N leaching	**GHG**	**CH_4**	**N_2O**
stock units	1.971*** (0.135)	379.8*** (4.295)	287.3*** (2.520)	92.48*** (3.332)
stock units squared	−0.0401*** (0.00531)	−0.726*** (0.169)	−0.347*** (0.0992)	−0.379** (0.131)
rainfall	−0.00162 (0.000921)	−0.0775** (0.0294)	−0.0167 (0.0172)	−0.0608** (0.0228)
temperature	0.164 (0.148)	26.30*** (4.713)	9.980*** (2.765)	16.32*** (3.656)
topography = non-flat hill	−0.177 (0.520)	−25.70 (16.57)	−20.93* (9.724)	−4.763 (12.86)
soil = peat	0.896 (4.953)	−33.41 (157.9)	−24.85 (92.62)	−8.564 (122.5)
soil = pumice	1.359 (1.078)	0.970 (34.36)	12.67 (20.16)	−11.70 (26.66)
soil = recent YGE	0.342 (0.614)	−7.997 (19.56)	−2.395 (11.47)	−5.602 (15.17)
soil = sands	−3.209 (1.926)	−81.70 (61.39)	−26.97 (36.02)	−54.72 (47.63)
soil = volcanic	1.818 (0.934)	100.6*** (29.77)	30.20 (17.47)	70.37** (23.10)
south island	2.463*** (0.638)	25.93 (20.33)	−21.35 (11.93)	47.28** (15.77)
year = 2009-10	3.472*** (0.733)	17.89 (23.35)	15.32 (13.70)	2.571 (18.11)
year = 2010-11	3.793*** (0.713)	35.46 (22.73)	25.95 (13.34)	9.510 (17.63)
year = 2011-12	3.844*** (0.711)	56.38* (22.66)	38.77** (13.29)	17.61 (17.58)
N residual		−18.27*** (1.616)	−0.861 (0.948)	−17.41*** (1.254)
constant	−5.919** (2.191)	−239.5*** (69.84)	−75.65 (40.98)	−163.8** (54.18)
No. observations	404	404	404	404
R-squared	0.532	0.991	0.995	0.914
adjusted R-squared	0.515	0.991	0.995	0.911

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. Here GHG = methane + nitrous oxide, measured in T CO_2-equivalent.
Controls: topography = flat, soil = sedimentary.

5 Scenario analysis

The analysis so far gives direction and significance of the likely effect of nutrient leaching management effort on greenhouse gases but does not tell us the scale of the effect. To explore this we run several scenarios.

First, we transform $\hat{\epsilon}_{it}$ according to a monotone transformation:

$$e_{it} = 100 \times (\hat{\epsilon}_{it} - min(\hat{\epsilon}_{it})). \quad (3)$$

This transformation gives nothing but a more sensible scale of the measure of nutrient management effort. Farms with the lowest estimated N management effort are defined as having effort of zero. The variable provides a ranking of farms but the numerical value does not have an intuitive interpretation.

Next, we consider three following scenarios.[13]

1. Conservative: every farmer with current nutrient management effort below the median (50th percentile) increases his level of effort by half of the difference between the median and the current level.
2. Ambitious: every farmer with current nutrient management effort below the 85th percentile increases his effort level by half of the difference between the 85th percentile and his current effort level.
3. Extreme: every farmer with current nutrient management effort below the 85th percentile increases his effort level to the 85th percentile.

Table E5 summarises the mean N management effort for dairy farms and its implied mean GHG mitigation for each scenario.

Table E6 does the same thing for sheep/beef farms. Figures E7 and Es8 depict the shifts of N management effort distributions under each scenario.

For dairy farms, we simulate that for each one percent reduction in nitrogen leaching farmers are likely to reduce greenhouse gases by around 0.11%. Nitrous oxide falls by more than methane; 0.26 relative to 0.05. These levels of greenhouse gas co-benefits are stable across scenarios.

Preliminary results on sheep-beef farms suggest very similar GHG co-benefits: around 0.10% overall for each one percent reduction in nitrate leaching, almost zero for methane and 0.41% for nitrous oxide. These results are similarly stable across scenarios.

13 These are the same as the three scenarios used in Anastasiadis and Kerr (2013).

Table 5: Scenario analysis of N management effort for dairy farms

Scenario	Mean N mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−7.30%	−0.81%	−0.38%	−1.94%
Ambitious	−23.47%	−2.61%	−1.21%	−6.23%
Extreme	−46.93%	−5.22%	−2.42%	−12.47%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Figure 7: Shift of N management effort distribution for dairy farms.

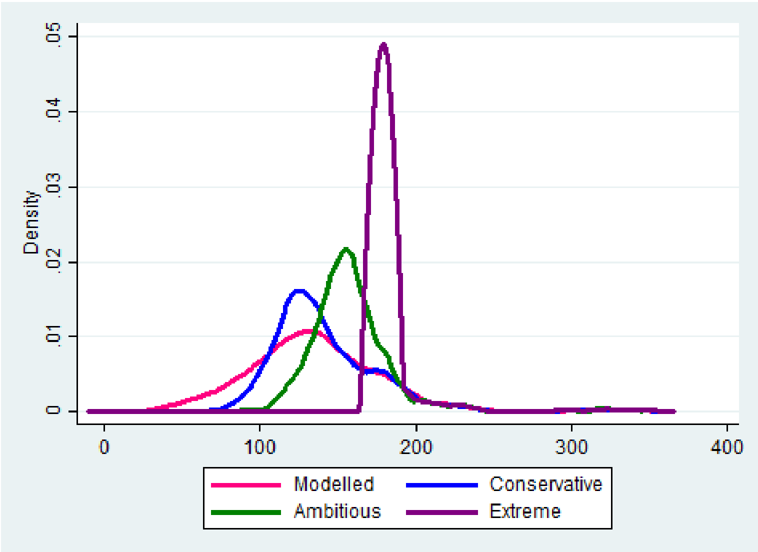
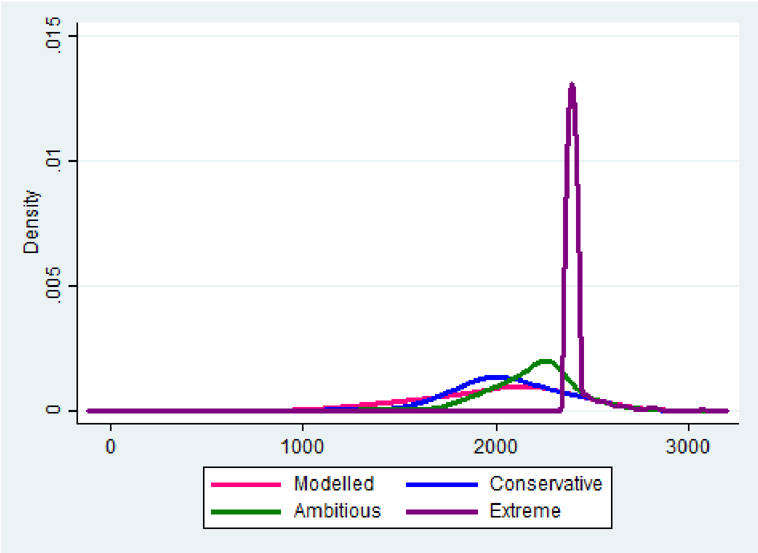


Table 6: Scenario analysis of N management effort for sheep/beef farms

Scenario	Mean N mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−5.79%	−0.59%	−0.04%	−2.41%
Ambitious	−12.03%	−1.23%	−0.08%	−5.01%
Extreme	−24.06%	−2.46%	−0.15%	−10.02%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Figure 8: Shift of N management effort distribution for sheep/beef farms.



Conclusion

In this paper we use a new dataset and a data driven approach as an alternative method to consider the potential for on-farm mitigation of nitrate leaching and phosphorus loss through use of existing practices, without changes in levels of production. We find estimates of nitrogen mitigation potential on dairy farms under conservative, ambitious and extreme scenarios that are very similar to those in (Anastasiadis & Kerr 2013). For sheep/beef farms we find nitrogen mitigation potential that is around half that on dairy farms. We are less confident about our estimates for potential mitigation of P-loss but they suggest similar potential for mitigation on dairy (around 30% in the 'ambitious' scenario) and half on sheep/beef farms (6% in the 'ambitious' scenario). These P results may however be heavily driven by correlations between unexplained low levels of N and P.

We find modest co-benefits from control of nitrogen leaching for reductions in greenhouse gases through changes to reduce nitrogen leaching per unit of product produced within current farm management practices. A one percent reduction in nitrogen leaching leads to around a quarter of a percent reduction in nitrous oxide and a tiny reduction in methane. Our 'ambitious' scenario suggests that dairy (sheep/beef) farmers might reduce nitrogen leaching by 23.5% (12%) and total greenhouse gases by 2.6% (1.2%) without changing production levels.

These reductions represent only one channel of effect of freshwater policy, but do suggest that freshwater policy that primarily focuses on changes in management within existing pastoral land use and currently used practices may have very limited effects on greenhouse gases.

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Appendix

Distributions of Product Per unit Pollution for Sheep/Beef farms

Figure 9: Distribution of Stock units per unit of Nitrogen leached on sheep/beef farms.

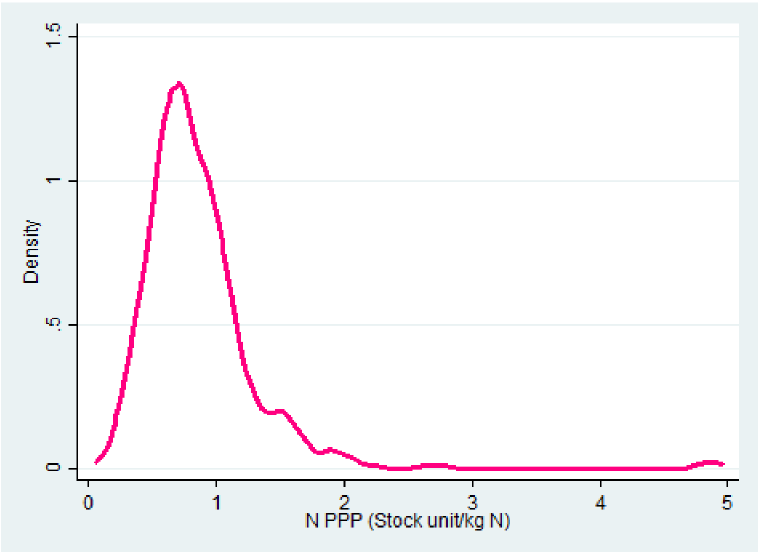
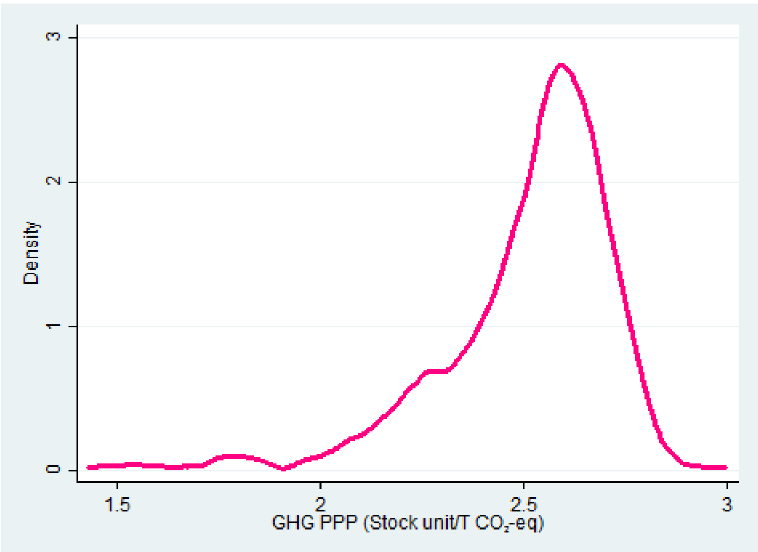


Figure 10: Distribution of stock units per unit of GHGs on sheep/beef farms.



Direct P analysis for dairy farms

Appendix Table 1: P regression results for dairy farms

	Step 1	Step 2		
	log(P loss)	**log(GHG)**	**log(CH_4)**	**log(N_2O)**
log(milk solids)	−0.0384	0.727***	0.728***	0.726***
	(0.111)	(0.0274)	(0.0282)	(0.0420)
log(rainfall)	−0.139	−0.0602	−0.0632	−0.0732
	(0.146)	(0.0359)	(0.0369)	(0.0550)
log(temperature)	0.769*	−0.0511	−0.0132	−0.140
	(0.303)	(0.0747)	(0.0768)	(0.114)
topography = non-flat hill	−0.0690	0.000766	0.00111	−0.00324
	(0.0758)	(0.0187)	(0.0192)	(0.0286)
soil = peat	0.0727	0.0629	0.0619	0.0568
	(0.259)	(0.0638)	(0.0655)	(0.0977)
soil = podzol	0.461*	0.0773	0.0863	0.0496
	(0.189)	(0.0466)	(0.0479)	(0.0714)
soil = pumice	0.360*	0.0780	0.0825	0.0747
	(0.174)	(0.0428)	(0.0440)	(0.0656)
soil = recent YGE	0.165	0.0560*	0.0498*	0.0778*
	(0.0916)	(0.0226)	(0.0232)	(0.0346)
soil = sands	−0.120	0.0805	0.0342	0.174**
	(0.176)	(0.0435)	(0.0447)	(0.0666)
soil = volcanic	0.221**	0.0719***	0.0754***	0.0660*
	(0.0806)	(0.0199)	(0.0204)	(0.0304)
log(cows wintered off)	0.00372	−0.0109**	−0.00805*	−0.0174**
	(0.0144)	(0.00355)	(0.00365)	(0.00544)
log(dairy replacements)	−0.0107	0.0731***	0.0770***	0.0677***
	(0.0339)	(0.00836)	(0.00859)	(0.0128)
year = 2009-10	−0.113	−0.0119	−0.0126	−0.0127
	(0.0862)	(0.0212)	(0.0218)	(0.0326)
year = 2010-11	−0.0761	−0.0491*	−0.0486*	−0.0469
	(0.0781)	(0.0193)	(0.0198)	(0.0295)
year = 2011-12	−0.0225	−0.0581**	−0.0489*	−0.0813**
	(0.0765)	(0.0189)	(0.0194)	(0.0289)
south island	−0.292**	−0.0333	−0.0410	−0.0236
	(0.0907)	(0.0224)	(0.0230)	(0.0343)
DCD used	−0.127	−0.0897**	−0.0198	−0.297***
	(0.111)	(0.0274)	(0.0281)	(0.0419)
Irrigated	0.579***	0.0560	0.00464	0.178***
	(0.118)	(0.0291)	(0.0299)	(0.0446)
P residual		−0.0512***	−0.0353**	−0.0940***
		(0.0129)	(0.0133)	(0.0198)
constant	−0.817	9.776***	9.395***	8.753***
	(1.050)	(0.259)	(0.266)	(0.397)
No. observations	384	384	384	384
R-squared	0.237	0.751	0.727	0.638
adjusted R-squared	0.199	0.738	0.713	0.619

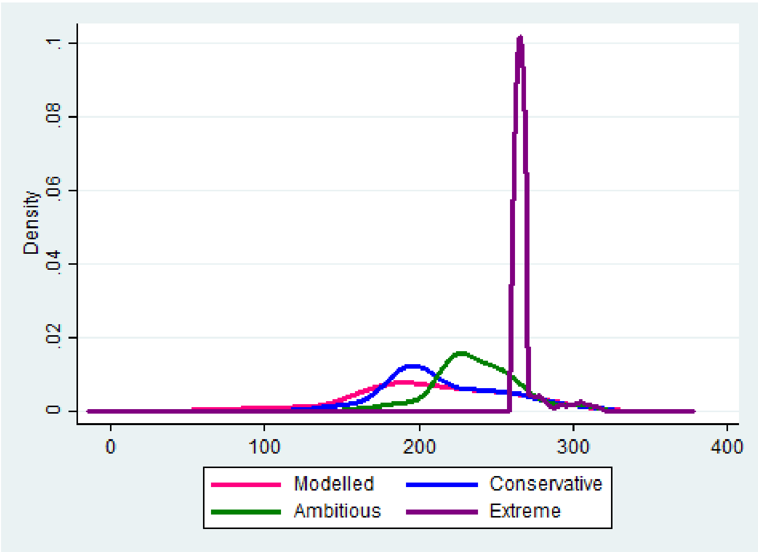
Note: * p<0.05, ** p<0.01, *** p<0.001. GHG = methane + nitrous oxide, measured in T CO_2-equivalent. Controls: topography = flat, soil = sedimentary.

Appendix Table 2: Scenario analysis of P management effort for dairy farms

Scenario	Mean P mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−10.20%	−0.52%	−0.36%	−0.96%
Ambitious	−30.42%	−1.56%	−1.07%	−2.86%
Extreme	−60.84%	−3.11%	−2.15%	−5.72%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Appendix Figure 1: Shift of P residual distribution for dairy farms.



Direct P analysis for sheep/beef farms

Appendix Table 3: P regression results for sheep/beef farms

	Step 1	Step 2		
	P loss	GHG	CH_4	N_2O
stock units	0.0510* (0.0240)	379.8*** (4.817)	287.3*** (2.500)	92.48*** (3.996)
stock units squared	−0.00126 (0.000945)	−0.726*** (0.190)	−0.347*** (0.0984)	−0.379* (0.157)
rainfall	0.000435** (0.000164)	−0.0775* (0.0329)	−0.0167 (0.0171)	−0.0608* (0.0273)
temperature	−0.0187 (0.0263)	26.30*** (5.285)	9.980*** (2.743)	16.32*** (4.384)
topography = non-flat hill	0.0311 (0.0926)	−25.70 (18.59)	−20.93* (9.646)	−4.763 (15.42)
soil = peat	−0.569 (0.882)	−33.41 (177.0)	−24.85 (91.87)	−8.564 (146.8)
soil = pumice	−0.265 (0.192)	0.970 (38.53)	12.67 (20.00)	−11.70 (31.96)
soil = recent YGE	−0.153 (0.109)	−7.997 (21.93)	−2.395 (11.38)	−5.602 (18.19)
soil = sands	0.136 (0.343)	−81.70 (68.84)	−26.97 (35.73)	−54.72 (57.11)
soil = volcanic	−0.226 (0.166)	100.6** (33.39)	30.20 (17.33)	70.37* (27.69)
south island	−0.748*** (0.114)	25.93 (22.79)	−21.35 (11.83)	47.28* (18.91)
year = 2009-10	0.0791 (0.131)	17.89 (26.19)	15.32 (13.59)	2.571 (21.72)
year = 2010-11	0.187 (0.127)	35.46 (25.49)	25.95 (13.23)	9.510 (21.14)
year = 2011-12	0.289* (0.127)	56.38* (25.41)	38.77** (13.18)	17.61 (21.07)
P residual		−47.95*** (10.17)	−14.17** (5.279)	−33.78*** (8.438)
constant	0.565 (0.390)	−239.5** (78.32)	-75.65 (40.64)	−163.8* (64.96)
No. observations	404	404	404	404
R-squared	0.233	0.989	0.995	0.876
adjusted R-squared	0.205	0.989	0.995	0.871

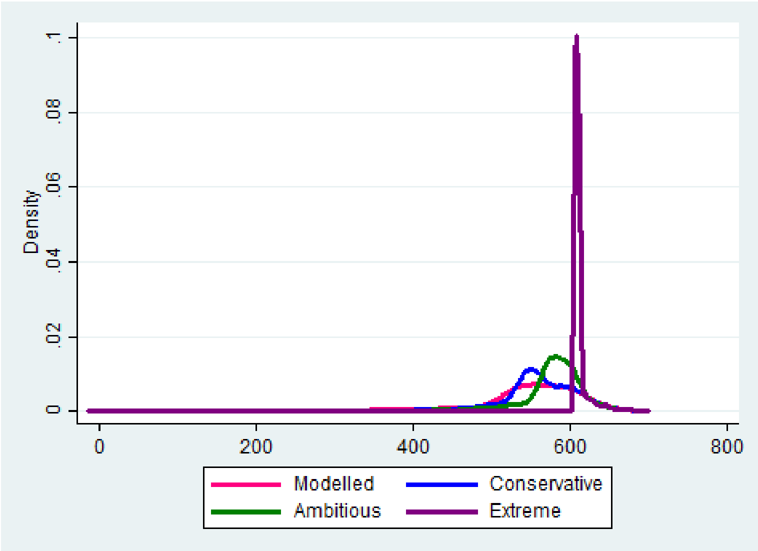
Note: * p<0.05, ** p<0.01, *** p<0.001. Here GHG = methane + nitrous oxide, measured in T CO_2-equivalent.
Controls: topography = flat, soil = sedimentary.

Appendix Table 4: Scenario analysis of P management effort for sheep/beef farms

Scenario	Mean P mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−3.24%	−0.24%	−0.09%	−0.73%
Ambitious	−6.37%	−0.47%	−0.18%	−1.43%
Extreme	−12.74%	−0.95%	−0.37%	−2.86%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Appendix Figure 2: Shift of P residual distribution for sheep/beef farms.



Indirect N analysis for dairy farms

To test for robustness and explore further we test the P-loss management effort proxy as an explanator in the N leaching equation. This is an attempt to isolate co-benefits driven solely by differences in N management. We find that those with unexplained low P loss also have lower nitrogen leaching but the impacts on GHGs are unaffected. These results hold for both dairy and sheep/beef farms.

Appendix Table 5: Repeated two-step N regression results for dairy farms

	Step 1	Step 2			
		Step 1	Step 2		
	log(P loss)	log(N leaching)	log(GHG)	log(CH_4)	log(N_2O)
log(milk solids)	−0.0384 (0.111)	0.675*** (0.0954)	0.727*** (0.0262)	0.728*** (0.0281)	0.726*** (0.0358)
log(rainfall)	−0.139 (0.146)	−0.298* (0.125)	−0.0602 (0.0343)	−0.0632 (0.0368)	−0.0732 (0.0469)
log(temperature)	0.769* (0.303)	−0.0736 (0.260)	−0.0511 (0.0714)	−0.0132 (0.0767)	−0.140 (0.0976)
topography = non-flat hill	−0.0690 (0.0758)	−0.0856 (0.0651)	0.000766 (0.0179)	0.00111 (0.0192)	−0.00324 (0.0244)
soil = peat	0.0727 (0.259)	0.177 (0.222)	0.0629 (0.0610)	0.0619 (0.0654)	0.0568 (0.0833)
soil = podzol	0.461* (0.189)	0.125 (0.162)	0.0773 (0.0446)	0.0863 (0.0478)	0.0496 (0.0609)
soil = pumice	0.360* (0.174)	0.168 (0.149)	0.0780 (0.0409)	0.0825 (0.0439)	0.0747 (0.0559)
soil = recent YGE	0.165 (0.0916)	0.0749 (0.0787)	0.0560** (0.0216)	0.0498* (0.0232)	0.0778** (0.0295)
soil = sands	−0.120 (0.176)	0.131 (0.151)	0.0805 (0.0416)	0.0342 (0.0446)	0.174** (0.0568)
soil = volcanic	0.221** (0.0806)	−0.0248 (0.0692)	0.0719*** (0.0190)	0.0754*** (0.0204)	0.0660* (0.0259)
log(cows wintered off)	0.00372 (0.0144)	−0.0238 (0.0124)	−0.0109** (0.00339)	−0.00805* (0.00364)	−0.0174*** (0.00464)
log(dairy replacements)	-0.0107 (0.0339)	0.0831** (0.0291)	0.0731*** (0.00799)	0.0770*** (0.00857)	0.0677*** (0.0109)
year = 2009-10	−0.113 (0.0862)	−0.00514 (0.0740)	−0.0119 (0.0203)	-0.0126 (0.0218)	−0.0127 (0.0277)
year = 2010-11	−0.0761 (0.0781)	−0.0600 (0.0671)	−0.0491** (0.0184)	−0.0486* (0.0198)	−0.0469 (0.0251)
year = 2011-12	−0.0225 (0.0765)	−0.135* (0.0657)	-0.0581** (0.0180)	−0.0489* (0.0194)	−0.0813** (0.0246)
south island	−0.292** (0.0907)	−0.293*** (0.0779)	−0.0333 (0.0214)	−0.0410 (0.0230)	−0.0236 (0.0292)
DCD used	−0.327** (0.0999)	−0.138 (0.112)	−0.0957** (0.0289)	−0.0267 (0.0296)	−0.302*** (0.0437)
irrigated	0.579*** (0.118)	−0.0273 (0.101)	0.0560* (0.0278)	0.00464 (0.0298)	0.178*** (0.0380)
P residual		−0.209*** (0.0450)			
N residual			−0.103*** (0.0144)	−0.0447** (0.0154)	−0.255*** (0.0196)
constant	−0.817 (1.050)	6.175*** (0.902)	9.776*** (0.248)	9.395*** (0.266)	8.753*** (0.338)
N	384	384	384	384	384
R-squared	0.237	0.259	0.773	0.728	0.737
adjusted R-squared	0.199	0.220	0.761	0.714	0.723

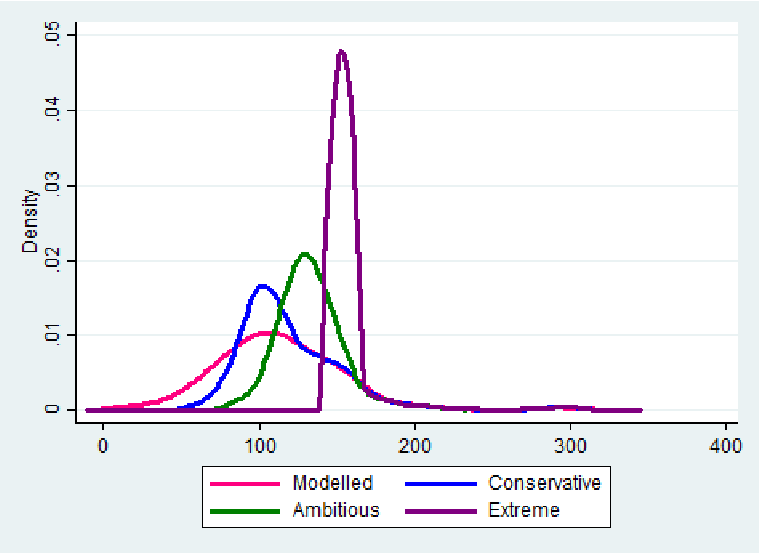
Note: * p<0.05, ** p<0.01, *** p<0.001. GHG = methane + nitrous oxide, measured in ton CO_2-equivalent. Controls: topography = flat, soil = sedimentary.

Appendix Table 6: Scenario analysis of N management effort for dairy farms

Scenario	Mean N mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−7.13%	−0.74%	−0.32%	−1.82%
Ambitious	−21.72%	−2.24%	−0.97%	−5.53%
Extreme	−43.43%	−4.48%	−1.94%	−11.06%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Appendix Figure 3: Shift of N residual distribution for dairy farms.



Indirect N analysis for sheep/beef farms

Appendix Table 7: Repeated two-step N regression results for sheep/beef farms

	Step 1	Step 2			
		Step 1	Step 2		
	P loss	**N leaching**	**GHG**	**CH_4**	**N_2O**
stock unit	0.0510* (0.0240)	1.971*** (0.133)	379.8*** (4.389)	287.3*** (2.522)	92.48*** (3.407)
stock unit squared	−0.00126 (0.000945)	−0.0401*** (0.00523)	−0.726*** (0.173)	−0.347*** (0.0993)	−0.379** (0.134)
rainfall	0.000435** (0.000164)	−0.00162 (0.000907)	−0.0775* (0.0300)	−0.0167 (0.0172)	−0.0608** (0.0233)
temperature	−0.0187 (0.0263)	0.164 (0.146)	26.30*** (4.815)	9.980*** (2.767)	16.32*** (3.738)
topography = non-flat hill	0.0311 (0.0926)	−0.177 (0.512)	-25.70 (16.93)	−20.93* (9.732)	−4.763 (13.15)
soil = peat	−0.569 (0.882)	0.896 (4.878)	−33.41 (161.3)	−24.85 (92.69)	−8.564 (125.2)
soil = pumice	−0.265 (0.192)	1.359 (1.062)	0.970 (35.11)	12.67 (20.18)	−11.70 (27.25)
soil = recent YGE	−0.153 (0.109)	0.342 (0.604)	−7.997 (19.98)	−2.395 (11.48)	−5.602 (15.51)
soil = sands	0.136 (0.343)	−3.209 (1.897)	−81.70 (62.72)	−26.97 (36.05)	−54.72 (48.69)
soil = volcanic	−0.226 (0.166)	1.818* (0.920)	100.6** (30.42)	30.20 (17.48)	70.37** (23.61)
year = 2009-10	0.0791 (0.131)	3.472*** (0.722)	17.89 (23.86)	15.32 (13.71)	2.571 (18.52)
year = 2010-11	0.187 (0.127)	3.793*** (0.702)	35.46 (23.22)	25.95 (13.35)	9.510 (18.03)
year = 2011-12	0.289* (0.127)	3.844*** (0.700)	56.38* (23.15)	38.77** (13.30)	17.61 (17.97)
south island	−0.748*** (0.114)	2.463*** (0.628)	25.93 (20.77)	−21.35 (11.94)	47.28** (16.12)
P residual		−1.012*** (0.280)			
N residual			−17.29*** (1.678)	−0.420 (0.965)	−16.87*** (1.303)
constant	0.565 (0.390)	−5.919** (2.158)	−239.5*** (71.35)	−75.65 (41.01)	−163.8** (55.39)
N	404	404	404	404	404
R-squared	0.233	0.547	0.991	0.995	0.910
adjusted R-squared	0.205	0.529	0.990	0.995	0.906

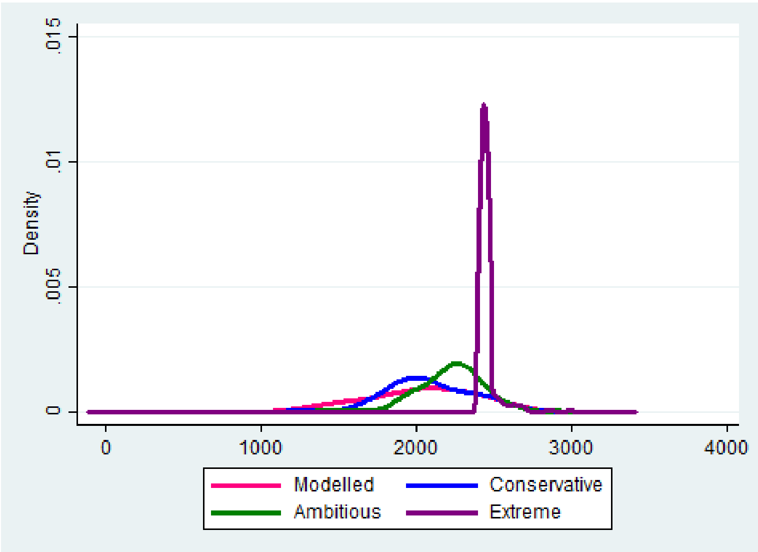
Note: * p<0.05, ** p<0.01, *** p<0.001. Here GHG = methane + nitrous oxide, measured in ton CO_2-equivalent.
Controls: topography = flat, soil = sedimentary.

Appendix Table 8: Scenario analysis of N management effort for sheep/beef farms

Scenario	Mean N mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−5.22%	−0.51%	−0.02%	−2.14%
Ambitious	−11.97%	−1.18%	−0.04%	−4.91%
Extreme	−23.94%	−2.35%	−0.07%	−9.82%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Appendix Figure 411: Shift of N residual distribution for sheep/beef farms.



Indirect P analysis for dairy farms

Similar to the sections above, we include the N management effort residual in the P-loss equation in an attempt to isolate the effect of differences in P-loss management on GHGs. We find that the effect of changes in P-loss management on GHGs seems slightly smaller than our main estimates. In particular the effect on nitrous oxide reduces to around half of the previous estimate.

Appendix Table 9: Repeated two-step P regression results for dairy farms

	Step 1	Step 2			
		Step 1	Step 2		
	log(N leaching)	**log(P loss)**	**log(GHG)**	**log(CH_4)**	**log(N_2O)**
log(milk solids)	0.675*** (0.0981)	−0.0384 (0.108)	0.727*** (0.0278)	0.728*** (0.0283)	0.726*** (0.0430)
log(rainfall)	−0.298* (0.129)	−0.139 (0.142)	−0.0602 (0.0364)	−0.0632 (0.0371)	−0.0732 (0.0564)
log(temperature)	−0.0736 (0.268)	0.769** (0.295)	−0.0511 (0.0758)	−0.0132 (0.0772)	−0.140 (0.117)
topography = non-flat hill	−0.0856 (0.0669)	−0.0690 (0.0737)	0.000766 (0.0190)	0.00111 (0.0193)	−0.00324 (0.0293)
soil = peat	0.177 (0.228)	0.0727 (0.252)	0.0629 (0.0647)	0.0619 (0.0658)	0.0568 (0.100)
soil = podzol	0.125 (0.167)	0.461* (0.184)	0.0773 (0.0473)	0.0863 (0.0481)	0.0496 (0.0732)
soil = pumice	0.168 (0.153)	0.360* (0.169)	0.0780 (0.0434)	0.0825 (0.0442)	0.0747 (0.0672)
soil = recent YGE	0.0749 (0.0809)	0.165 (0.0891)	0.0560* (0.0229)	0.0498* (0.0233)	0.0778* (0.0355)
soil = sands	0.131 (0.156)	−0.120 (0.172)	0.0805 (0.0441)	0.0342 (0.0449)	0.174* (0.0683)
soil = volcanic	−0.0248 (0.0711)	0.221** (0.0784)	0.0719*** (0.0202)	0.0754*** (0.0205)	0.0660* (0.0312)
log(cows wintered off)	−0.0238 (0.0127)	0.00372 (0.0140)	−0.0109** (0.00360)	−0.00805* (0.00367)	−0.0174** (0.00558)
log(dairy replacements)	0.0831** (0.0299)	−0.0107 (0.0330)	0.0731*** (0.00848)	0.0770*** (0.00863)	0.0677*** (0.0131)
year = 2009-10	−0.00514 (0.0761)	−0.113 (0.0838)	−0.0119 (0.0216)	−0.0126 (0.0219)	−0.0127 (0.0334)
year = 2010-11	−0.0600 (0.0689)	−0.0761 (0.0760)	−0.0491* (0.0195)	−0.0486* (0.0199)	−0.0469 (0.0302)
year = 2011-12	−0.135* (0.0675)	−0.0225 (0.0744)	−0.0581** (0.0191)	−0.0489* (0.0195)	-0.0813** (0.0296)
south island	−0.293*** (0.0801)	−0.292** (0.0883)	−0.0333 (0.0227)	−0.0410 (0.0231)	−0.0236 (0.0351)
DCD used	−0.295** (0.0980)	−0.127 (0.108)	−0.0897** (0.0278)	−0.0198 (0.0283)	−0.297*** (0.0430)
irrigated	−0.0273 (0.104)	0.579*** (0.115)	0.0560 (0.0295)	0.00464 (0.0300)	0.178*** (0.0457)
N residual		−0.268*** (0.0577)			
P residual			−0.0296* (0.0135)	−0.0260 (0.0137)	−0.0409 (0.0209)
constant	6.175*** (0.927)	−0.817 (1.022)	9.776*** (0.263)	9.395*** (0.267)	8.753*** (0.407)
N	384	384	384	384	384
R-squared	0.215	0.279	0.744	0.724	0.620
adjusted R-squared	0.176	0.242	0.730	0.710	0.600

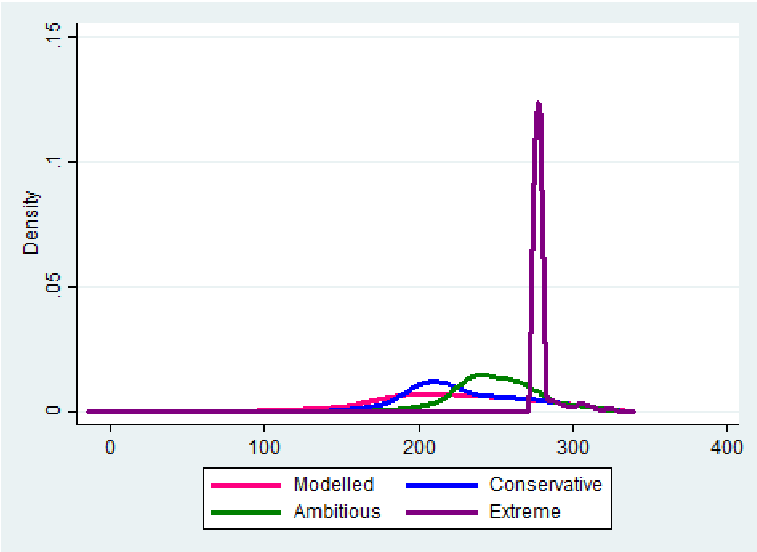
Note: * p<0.05, ** p<0.01, *** p<0.001. Here GHG = methane + nitrous oxide, measured in ton CO_2-equivalent.
Controls: topography = flat, soil = sedimentary.

Appendix Table 10: Scenario analysis of indirect P management effort for dairy farms

Scenario	Mean P mitigation	Implied mean GHG mitigation		
		GHG	CH_4	N_2O
Conservative	−10.46%	−0.31%	−0.27%	−0.43%
Ambitious	−29.88%	−0.89%	−0.78%	−1.22%
Extreme	−59.76%	−1.77%	−1.55%	−2.44%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Appendix Figure 5: Shift of P residual distribution for dairy farms.



Indirect P analysis for sheep/beef farms

Appendix Table 11: Repeated two-step P regression results for sheep/beef farms

	Step 1	Step 2			
		Step 1	Step 2		
	N leaching	**P loss**	**GHG**	**CH4**	**N2O**
stock unit	1.971*** (0.135)	0.0510* (0.0236)	379.8*** (4.900)	287.3*** (2.502)	92.48*** (4.058)
stock unit squared	−0.0401*** (0.00531)	−0.00126 (0.000931)	−0.726*** (0.193)	−0.347*** (0.0985)	−0.379* (0.160)
rainfall	−0.00162 (0.000921)	0.000435** (0.000162)	−0.0775* (0.0335)	−0.0167 (0.0171)	−0.0608* (0.0277)
temperature	0.164 (0.148)	-0.0187 (0.0259)	26.30*** (5.376)	9.980*** (2.745)	16.32*** (4.452)
topography = non-flat hill	−0.177 (0.520)	0.0311 (0.0912)	−25.70 (18.91)	−20.93* (9.654)	-4.763 (15.66)
soil = peat	0.896 (4.953)	−0.569 (0.869)	−33.41 (180.1)	−24.85 (91.94)	−8.564 (149.1)
soil = pumice	1.359 (1.078)	−0.265 (0.189)	0.970 (39.20)	12.67 (20.01)	−11.70 (32.46)
soil = recent YGE	0.342 (0.614)	−0.153 (0.108)	−7.997 (22.31)	−2.395 (11.39)	−5.602 (18.48)
soil = sands	−3.209 (1.926)	0.136 (0.338)	−81.70 (70.04)	−26.97 (35.76)	−54.72 (58.00)
soil = volcanic	1.818 (0.934)	−0.226 (0.164)	100.6** (33.96)	30.20 (17.34)	70.37* (28.13)
year = 2009-10	3.472*** (0.733)	0.0791 (0.129)	17.89 (26.64)	15.32 (13.60)	2.571 (22.06)
year = 2010-11	3.793*** (0.713)	0.187 (0.125)	35.46 (25.93)	25.95 (13.24)	9.510 (21.47)
year = 2011-12	3.844*** (0.711)	0.289* (0.125)	56.38* (25.85)	38.77** (13.20)	17.61 (21.40)
south island	2.463*** (0.638)	−0.748*** (0.112)	25.93 (23.19)	−21.35 (11.84)	47.28* (19.20)
N residual		−0.0321*** (0.00889)			
P residual			−30.45** (10.52)	−13.75* (5.372)	−16.70 (8.713)
constant	−5.919** (2.191)	0.565 (0.384)	−239.5** (79.67)	−75.65 (40.68)	−163.8* (65.98)
N	404	404	404	404	404
R-squared	0.532	0.258	0.989	0.995	0.872
adjusted R-squared	0.515	0.229	0.988	0.995	0.867

Note: * p<0.05, ** p<0.01, *** p<0.001. GHG = methane + nitrous oxide, measured in ton CO_2-equivalent.
Controls: topography = flat, soil = sedimentary

Appendix Table 12: Scenario analysis of indirect P management effort for sheep/beef farms

Scenario	Mean P mitigation	Implied mean GHG mitigation		
		GHG	CH4	N2O
Conservative	−3.08%	−0.15%	−0.09%	−0.35%
Ambitious	−6.23%	−0.30%	−0.18%	−0.71%
Extreme	−12.46%	−0.61%	−0.36%	−1.42%

Note: GHG = CH_4 + N_2O in T CO_2-equivalent measure.

Appendix Figure 6: Shift of P residual distribution for sheep/beef farms.