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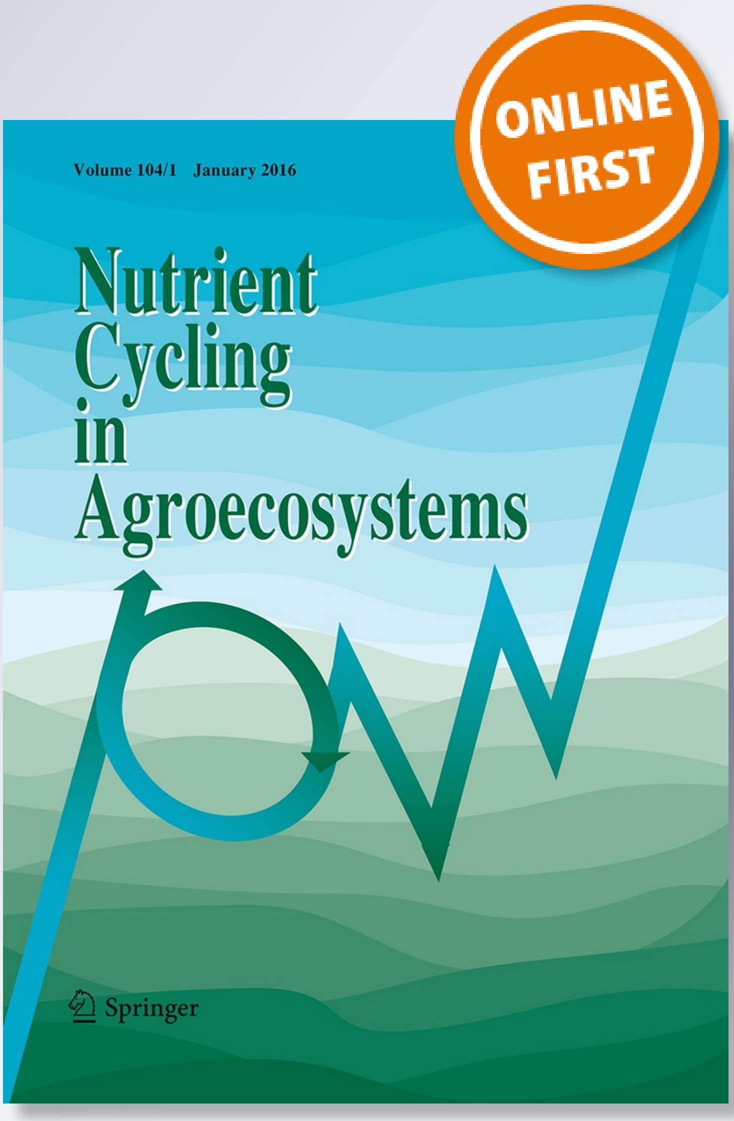
Nutrient Cycling in Agroecosystems
(formerly Fertilizer Research)

ISSN 1385-1314

Nutr Cycl Agroecosyst
DOI 10.1007/s10705-016-9767-0



Manuscript Title:

Adapting feeding methods for less nitrogen pollution from pig and dairy cattle farming: Abatement costs and uncertainties

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Acknowledgements

This paper is a contribution to the International Nitrogen Initiative. It takes advantage of the results of the FarmClim project funded by the Austrian Climate Research Programme (ACRP). The authors wish to thank Maria Lohring for careful language editing. MP acknowledges a scholarship received from the University of Graz.

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Abstract

This study assesses abatement costs of three measures aimed at reducing nitrogen (N) emissions from livestock production: protein-adjusted feeding strategies for pigs, and higher-quality forage for dairy cattle. In a partial cost approach, we quantified the effect of different measures on N losses and production costs. We accounted for emissions of NH_3, N_2O and NO from animal housing, manure storage, manure application, and from soils. Uncertainties related to volatile prices and assumptions about excretion rates and emission factors were assessed in a Monte Carlo simulation. Covering variability of individual input parameters, this uncertainty assessment addresses a fundamental gap in current decision support on N loss reduction measures. For the scenarios investigated, average N abatement costs at farm level were negative and represented net benefits to farmers: In pig husbandry, adapting feeding practices in most individual situations resulted in net benefits, both for three-phase feeding [min -35, max +5, mean -14 €/kg N abated] and optimised single-phase feeding [min -52, max +4, mean -21 €/kg N abated]. In dairy production, N abatement by improved forage quality proved invariably more economic than current practice [min -40, max -11, mean -21 €/kg N abated]. As shown in this study, N abatement costs can serve as a framework for comparing the cost-effectiveness and feasibility of N loss reduction measures within and between livestock production systems. This is in turn critical when informing practitioners and providing policy support on workable strategies for reducing the N footprint of animal husbandry.

Keywords: nitrogen losses, nitrogen abatement cost, Monte Carlo simulation, nitrogen use efficiency (NUE), pig fattening, dairy forage

1. Introduction

Human influence on the global nitrogen (N) cycle is substantial, with agriculture as the largest contributor. Reactive N refers to those chemical forms of N that are available to plants and animals. Variable proportions of the reactive N used as fertiliser for feed crop production are eventually released back into the environment during the storage and decomposition of animal manures. Inefficient manure management practices and excessive application rates increase emissions of reactive N, with a range of detrimental effects on ecosystems, human health and global climate (Erisman et al. 2013; Fowler et al. 2013; Galloway et al. 2004; Galloway et al. 2008). In response to these challenges, which apply particularly to intensive, industrialized production systems, a broad range of measures has been proposed for different agricultural sectors to become more nitrogen-efficient. In arable farming, cover crops and optimised low-N fertilisation have proven effective at reducing N losses (Dalgaard et al. 2014; Döhler et al. 2011; Newell Price et al. 2011; Reis et al. 2015). For animal husbandry effective N loss reduction has been demonstrated for instance for optimised livestock feeding and for improved manure management (i.e. removal, storage, and spreading techniques) (Dalgaard et al. 2014; Döhler et al. 2011; Newell Price et al. 2011; Reis et al. 2015; Rotz 2004). Animal nutrition has been highlighted as a priority area for reducing environmental N pollution from livestock production (Aarnink and Verstegen 2007; Klimont and Brink 2004). Increasing the N use efficiency (NUE) of common husbandry systems by adapting feeding methods is therefore the focus of this paper.

In pig farming, feeding practices can be adapted to minimise N excretion and N losses from manure management by phase feeding, i.e. adjusting feed composition according to the pig's physiological needs at different growth stages; supplementing diets with limiting amino acids; reducing crude protein intake; and shifting N excretion from urine to faeces by adjusting feed composition (Aarnink and Verstegen 2007; Dourmad and Jondreville 2007; Jongebreur et al. 2005; Nahm 2002; van Vuuren et al. 2015).

Under production conditions in industrialised countries, reducing N intake by dairy cattle has the potential to decrease N excretion and N losses without compromising milk production (Bittman et al. 2014; Powell 2014). One approach to reducing emissions of reactive N and greenhouse gases (GHG) from dairy cattle farming is to increase milk yields to an extent that outweighs additional N excretion. This can be achieved by enhancing the energy density of the feed, e.g. through a higher content of grain-concentrates in compound feeds or higher-quality forage (Gruber et al. 1999; Hörtenhuber et al. 2010; Ryan et al. 2011). However, the effect of more concentrate might be partially counteracted by additional emissions from soils and fertiliser use in the production of such feeds (Hörtenhuber et al. 2010). This approach also raises questions regarding animal health as well as ethical concerns, since the capacity of dairy cows to digest concentrates is limited, and using grains as livestock feed rather than for human nutrition is questionable (Ertl et al. 2014; Hörtenhuber et al. 2011). To address these concerns, Hörtenhuber et al. (2010) proposed to focus efforts on finding alternative ways to improve the nutrient and energy density of forage. One measure which can achieve this, while avoiding the dilemma of grain-based feeds, is to increase the number of grass cuts per year (Gruber et al. 1999; Gruber and Pötsch 2006).

Using N inefficiently by excess feeding to livestock not only contributes to environmental pollution via increased N excretion; expenses for surplus feed also unnecessarily increase costs to farmers. Feed costs generally account for a large proportion of total costs of animal production (Finneran et al. 2012; Powell et al. 2013). Many studies focus on possible reductions of negative environmental effects, without consistently considering the economic viability of those measures at farm level (Aarnink and Verstegen 2007; Dourmad and

Jondreville 2007; Nahm 2002; Ryan et al. 2011). Other studies analyse economic effects of different feeding strategies and strive for economic optimisation, but lack detailed discussion of environmental implications (Finneran et al. 2012; Marston et al. 2011; Niemi et al. 2010; Vibart et al. 2012). Discussions which examine and synthesise both aspects, i.e. the potential environmental benefits and the economic implications of different measures, are scarce (see e.g. van Vuuren et al. (2015) who review the economics of low-N feeding strategies). Such analyses, however, are vital for setting policy priorities: A given N abatement measure will appear more attractive to farmers, and will thus more likely be adopted, if there is evidence supporting its economic feasibility and benefits. On the other hand, if the reduction of N emissions is not profitable for farmers under current conditions, additional policy incentives (e.g. subsidies, support schemes) might be needed to increase uptake.

The recently completed Austrian research project FarmClim - “Farming for a better climate” (Amon et al. 2014) aimed to identify cost-effective and practical strategies for farmers to increase the nitrogen-efficiency and to reduce the GHG emissions of their production systems. Measures considered for animal husbandry included phase feeding for pigs, improved dairy cattle diets, and anaerobic digestion of animal manures. For crop production, increasing the use of legumes in crop rotations, and optimising fertiliser input were addressed. In close collaboration between stakeholders (researchers as well as agricultural institutions and extension services) agricultural measures were assessed and discussed from different perspectives in a transdisciplinary and participatory process. The livestock part of FarmClim focussed in particular on the situation of farmers, as a central aim was to provide practical guidance at farm level.

The objective of the present paper is to assess farm-level N abatement potentials and costs of three key measures developed for animal husbandry in the FarmClim project (Amon et al. 2014): optimised single phase feeding and three-phase feeding for pigs, and higher-quality forage for dairy cattle. A Monte Carlo uncertainty analysis was conducted to account for uncertainties due to volatility in demand and market prices as well as for variability in milk yield, N excretion and N emissions. Reducing the dependency on specific assumptions of input data, this uncertainty analysis enables the consideration of a broader range of production characteristics. We first calculated partial gross margins per unit of product and then derived changes in gross margins between different measures, by comparing additional costs and benefits at farm level. In order to estimate average N abatement costs for each of the measures, we assessed potential reductions in N excretion and in the subsequent volatilisation of NH_3, N_2O and NO.

2. Methods

2.1. Scope of analysis

This study addresses exemplary, individual pig and dairy farms, aiming to provide information for decision making in practice. Therefore cost analyses focus on private costs and benefits for farmers. Calculating average abatement costs for specific measures, we did not assess abatement potentials for the entire sector of agriculture nationally or internationally. Furthermore, because individual farms are considered as price takers within the market, complex market dynamics, such as the consequences of many farmers changing their activities, were not accounted for within this study. Likewise, sectoral, national or international developments and interactions are neglected. In line with this farm perspective, only those emissions related directly to the farming practice were assessed (i.e., animal housing and manure management).

Based on some assumptions about principal production traits that are in line with EU averages (see below for details), we were able to simulate a wide of range of production situations by independently and simultaneously varying several input variables in a Monte Carlo analysis (e.g. feed and product prices, N excretion rates, N emission factors). Data were sourced from agricultural extension services and guidelines, such as: the Austrian Federal Institute of Agricultural Economics (AWI 2015) for production traits and related costs, national statistical information from Statistics Austria (2014) mainly for input and output prices, and international guidelines for N excretion and emission factors (European Environment Agency (EEA) 2013; IPCC 2006a). Specific data used can be found in Table A.3 in the Annex. Additional input data were taken from the FarmClim project (Amon et al. 2014; Moser et al. 2013), and were further processed as detailed in the subsequent section.

2.2. N abatement through optimised diets: Measures and data

Pigs. Phase feeding systems adjust the diet in several phases, rather than providing feed of unchanged composition over the entire course of the fattening period. More specifically, the supply of protein as the main source of dietary N is matched to the changing physiological needs of the pig, thereby reducing excess supply and excretion of N. As the optimum dietary protein concentration decreases during the growth of a pig, phase feeding reduces N emissions without compromising growth performance (i.e. slaughter weight) (Dämmgen et al. 2011; Pomar et al. 2014; van Vuuren et al. 2015).

Phase feeding systems usually require additional investment in feeding technology. Such investment is only economically feasible for farms with a sufficiently long-term production perspective and economies of scale in cost savings. For farms with shorter planning horizons, optimisation measures that require upfront investment are often disproportionate to profit margins and hence not an option. That situation is faced by many small farms across Europe;

especially family farmers may not know whether their operations will be continued after their retirement. For such farms, a technologically simpler and more attractive option would be to optimise the feed mix in a traditional single-phase feeding system by reducing the overall protein content of the diet. This approach is generally less effective at reducing N losses than phase feeding. Nevertheless, we included optimised single-phase feeding in this analysis as it was the aim of our research to find N abatement methods that would be workable more generally in Europe.

For both pig feeding methods, it is important to bear in mind that reduced protein intake necessitates the supplementation of limiting essential amino acids. The resulting costs were included in our calculations.

We analysed the following scenarios for pig fattening (Table 1):

- a single-phase feeding system as the reference case (REF_pig),
- an optimised single-phase feeding system with reduced dietary crude protein content but supplementation of synthetic amino acids (S1_pig), and
- a three-phase feeding system with the same feed components as in S1_pig, with a further reduction of crude protein content (S2_pig).

All three scenarios were based on a total feed intake of 254 kg per fattening pig and a slaughter weight of 96 kg (AWI 2015). Thus, whereas the feed composition changes, the pigs' performance level remains constant. The production system was further characterised by a herd size of 450 fattening places with a turnover rate of 2.67, and an N excretion rate of 10.3 kg N per fattening place and year (AWI 2015; Umweltbundesamt 2014b). While this is based on Austrian sources to maintain internal consistency, the basic characteristics are in line with average EU values (see table A.1 in the Annex for information on N excretion and slaughter weight).

[Insert Table 1 here]

Dairy cattle. Forage quality can be improved by cutting grassland more frequently (Gruber et al. 1999). This results in a lower total dry matter yield of the cut grass, but at the same time increases forage intake, digestibility and protein content (Gruber et al. 1999; Gruber and Pötsch 2006). The higher protein content leads to increases in total N intake and N excretion, which seems to counteract the intended reduction of N losses at first sight. However, the larger amount of energy provided by higher-quality forage supports higher milk yields, and thereby reduces N excretion per kg milk produced (Ertl et al. 2014; Steinwidder and Guggenberger 2003). For dairy cattle, we analysed two feeding options: a reference case (REF_milk) with medium-quality forage from three grass cuts per year and a mixture of concentrate feed; and a scenario with high-quality forage (S_milk), where the frequency of grass cuts was increased to four. This results in a higher intake of grass-silage and hay. Due to the conceptual assumption of a constant share of each forage component in the total diet (i.e., 65% grass silage, 20% maize silage, 15% hay), intake of maize silage is also increased. In addition, S_milk included the same ration of concentrate feed as REF_milk (see Table 2). In contrast to the pig scenarios, both feed intake and performance (i.e., milk yield) are affected by the measure. We assumed predominantly grass-based diets with limited supplementation of concentrate feed, and local climatic conditions that allow for frequent grass-cutting and correspondingly high forage quality. We assumed baseline milk yield (6500 kg/cow/year) and N excretion (100 kg N/cow/year) to correspond to the EU-28 average (6538 kg milk/cow/year and 108.07 kg N/cow/year, respectively; see Table A.2 in the Annex for country data). Our calculation of attainable milk yield was based on following assumptions: From their diet, dairy cattle need to obtain 13 870 MJ worth of net energy for lactation (NEL) for maintenance, and an additional 700 MJ NEL during the preparation phase for lactation. That latter phase hence requires a more energy-dense diet, i.e. one with a larger concentrate component. Any further energy intake is available for milk production, where 3.3 MJ NEL are required for each kg of milk produced (AWI 2015).

[Insert Table 2 here]

2.3. Nitrogen abatement

Nitrogen abatement is defined as the total amount of N emissions that can be avoided by implementing a given measure, in comparison to the reference case. To quantify these "avoided losses" of N to the environment, emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitric oxide (NO) were derived from N excretion rates and emission factors. Thus, the terms "N emission" (or "N losses") and "N abated" in this paper always refer to the sum of emissions of these three N species. Emission sources considered here were animal housing and manure management (storage and application to land including direct emissions from soil) (IPCC 2006a). The analysis hence incorporated the entire chain of N emissions which arise from livestock production and which are directly attributable to individual farms. Upstream effects, e.g. of feed or fuel production, which would typically be included in life cycle analyses (LCA), were not considered in this study.

N emissions for both reference cases (REF_pig and REF_milk), as given in Table A.3 in the Annex, were based on excretion rates and emission factors from Austria's national emission inventory reports (Umweltbundesamt 2014a, 2014b), on a regression model predicting dairy cow excretion (Gruber et al. 1999), and on international guidance documents (European Environment Agency (EEA) 2013, IPCC 2006a, 2006b). Our calculations further assumed the use of a liquid slurry system for manure management in all scenarios.

The reduction of ammonia emissions due to adjustments in feeding methods has been assessed in a range of experimental studies (Aarnink and Verstegen 2007; Dämmgen et al.

2011; Dourmad and Jondreville 2007; Pomar et al. 2014). Those studies provide a valuable baseline. However, due to the number of variables and lack of standards for experimental conditions, results are often only valid for very specific technical and geographical contexts. This unfortunately limits the extent to which those empirical studies can inform policy and practice elsewhere. For the same reasons, our calculations did not draw upon results from individual experimental studies. We instead took a simplified approach for approximating the change in N excretion:

For pigs, the reduction in N excretion can be derived from simple N balance considerations: When excess N supply in pig fattening diets is reduced (as described above), a given decrease in protein intake directly translates into a corresponding decrease in N excretion (Kornegay and Harper 1997). N emissions then decline accordingly, as they are calculated as percentages of N excretion.

In dairy systems, estimating N abatement is more complex: When milk yield is increased by raising the protein density of the diet, this inherently also increases N excretion. However, it is generally assumed that the resulting increase in N emissions is outweighed by the higher milk yields. National inventory reports (Umweltbundesamt 2014b) for instance estimate N emissions with a linear function, where N excretion exclusively depends upon milk yields. In reality, N excretion however also depends, among other factors, on the protein content of the diet (Gruber and Pötsch 2006; Pötsch 2006). Gruber et al. (1999) have developed a more detailed regression model, which predicts manure N concentrations and N excretion of dairy cows, based on forage and concentrate intake and on the corresponding crude protein and energy content of the diet. Their model was used here to estimate N excretion more accurately (Eq.1) (Gruber et al. 1999):

$$Ec_N = -0.6 + 0.106(IF * XP_F) + 1.153(IC * NEL_C) + 0.0605(XP_T * NEL_T) \quad \text{(Eq.1)}$$

where: Ec_N = excretion of N per cow (g/day); IF = intake of forage (kg DM); IC = intake of concentrate (kg DM); XP_F, XP_T = crude protein concentration of forage and total ration (g/kg DM); NEL_C, NEL_T = energy concentration of the concentrate and total ration (MJ/kg DM)

2.4. Cost calculation

When comparing the economic feasibility of different management practices, the most relevant changes in costs and benefits are those that directly result from the implementation of the measures in question. Standard costs of equipment, etc., can thus be omitted if they are constant (Rejesus and Hornbaker 1999; Ryan 2005). This simplifies the calculation and eliminates a source of bias and uncertainty, without compromising the validity and explanatory power of the results. While this partial cost approach has been criticised (Finneran et al. 2012), it is appropriate for the study at hand, as the purpose here was to assess costs and benefits of N abatement in relation to a certain reference situation, rather than determine general farm profitability, for which full cost accounting would have been required. In this vein, we did not quantify opportunity, follow-up or indirect costs and interactions, which are important elements for overall farm profitability assessments, but are not generally considered in gross margin calculations.

To reflect the private costs and benefits of different N abatement measures at farm level, we calculated partial gross margins (PGM) per unit of product, i.e. per kg meat or milk, for each feeding scenario. PGM was defined as revenues minus costs of production per unit sold. (*N.B.*: Costs must be directly related to the abatement measure). Partial gross margins hence represent the revenues available for covering the remaining costs which were unaffected by the measure, and to generate profit. The following costs were included: costs of the feed components, investment in phase feeding systems for S2_pig, and additional costs due to more frequent cutting for S_milk. These latter costs have been incorporated in the costs of forage provision and encompass seeds, fertilizer, crop protection, variable machinery costs, and labour costs. Revenues came from selling pork and milk at market prices. We ignored potential grants, subsidies, and any costs not practically related to the N abatement measures. Table A.3 in the Annex lists the specific data and references used, and equations 2 and 3 outline the calculation of gross margins for pig and milk production, respectively.

$$\pi_{pig} = \frac{1}{W}(p_{pig} * W - \sum pf_i * F_i - c_{invest}) \qquad \text{(Eq.2)}$$

Where: π_{pig} = partial gross margin per kg pork [€/kg]; W = slaughter weight of pig [kg]; p_{pig} = price of pork [€/kg]; pf_i = price of feed component *i* [€/kg]; F_i = intake of feed component *i* [kg/pig/year]; c_{invest} = investment cost, including costs of capital and depreciation per pig [€/pig/year].

$$\pi_{milk} = \frac{1}{M}(p_{milk} * M - \sum pf_i * F_i) \qquad \text{(Eq.3)}$$

Where: π_{milk} = partial gross margin per kg milk [€/kg]; M = milk yield [kg/cow/year]; p_{milk} = price of milk [€/kg]; pf_i = price of feed component *i* [€/kg]; F_i = intake of feed component *i* [kg/cow/year];

To derive average N abatement costs (AC), we calculated the differences in N losses and partial gross margins between the respective scenario and the reference case. Average abatement costs were then expressed as the difference in partial gross margin per kg N abated, compared to REF (equation 4). In this step, all costs and subsidies related to production in general (rather than to the specific measures) would cancel out; we therefore considered a detailed assessment of these aspects unnecessary. Commonly used in relevant literature for assessing individual abatement options (Bittman et al. 2014; Rößler et al. 2012; Van Vuuren et al. 2015), this measure of average on-farm abatement costs considers the implementation of one specific measure as a fixed “package” that results in a certain amount of emission reduction, rather than assuming that farmers gradually adjust their abatement efforts. In contrast, marginal abatement costs, which are the costs of abating one additional unit of emissions starting from a certain level, are used in national or sector economic analyses and to inform policymaking. For instance, marginal abatement cost curves can help to determine economically optimal levels of abatement, and are used for merit order ranking of different abatement measures (De Cara and Jayet 2011; Eory et al. 2013).

To account for interactions and co-benefits of simultaneously reducing NH_3, N_2O, and even NO, the measure of abatement costs basically refers to the sum of these N species. However, for reasons of comparability with other studies, separate AC for NH_3, N_2O and NO are indicated additionally. As the costs cannot reliably be attributed to different N species, these AC were derived by allocating all costs of the measures to each type of N emissions and thus contain considerable double counting of costs.

$$AC_i = \frac{\pi_i - \pi_{REF}}{N\_loss_i - N\_loss_{REF}} \qquad \text{(Eq.4)}$$

Where: AC_i = abatement cost for scenario i [€/kg N]; $\pi_{i,\,REF}$ = partial gross margin in scenario i and the reference case, respectively ([€/kg pork] and [€/kg milk], respectively); $N\_loss_{i,REF}$ = N losses in scenario i and the reference case, respectively ([kg N/kg pork] and [kg N/kg milk], respectively).

2.5. Uncertainty analysis

The parameters and assumptions first used to develop deterministic baselines (see section 2.4) are in reality linked with uncertainties, such as price fluctuations and variation in livestock performance and physiological characteristics (milk yield, N excretion). Furthermore, the uncertainty of N emission factors needs to be accounted for, as the exact amount of N emitted depends on a broad set of influencing factors and management practices.

To take these uncertainty aspects into consideration, we conducted a Monte Carlo uncertainty analysis. Monte Carlo analysis is a stochastic technique that uses random numbers and probability statistics to evaluate uncertain outcomes. More specifically, a randomly selected set of input values for uncertain parameters is fed into the simulation to derive related outputs. This procedure is repeated for numerous iterations (in our case 10 000), and finally allows to estimate output uncertainty by mapping the results as new output-probability distribution functions (Benke et al. 2007; Bergsdal et al. 2007). By introducing statistical distributions for uncertain and variable input parameters, Monte Carlo analysis reduces the dependency on single point estimates and assumptions (Bergsdal et al. 2007; Evans et al. 2007). To define these probability distribution functions (pdf's) for the market prices of pork, milk, barley, wheat, soybean meal and rapeseed meal, monthly prices from 2000 to 2010 were adjusted by the price index of animal and plant-based agricultural products, respectively (LKÖ 2013). This correction removed the deterministic element of the variation in prices, i.e. inflation, and only considered stochastic variation (see also Finneran et al. (2012), who used a more complex approach). Most of the price distributions did not meet all criteria for normal distribution. We therefore modelled the prices with continuous triangular distributions, based on the minimum, maximum and mode values of the index-adjusted monthly prices. A continuous triangular probability distribution was also assumed for the other stochastic variables (other feed components, investment cost, forage quality, milk yield, N excretion and emission factors), where no larger data sets or longer time series were available. Using triangular distributions to estimate probabilities under such data constraints is common practice (Evans et al. 2007), and has also been used for estimating emission factors (Lovett et al. 2008; Zehetmeier et al. 2014). The specific probability distribution functions used in our analysis, and the corresponding data sources, are summarised in Table A.3 in the Annex.

Correlations. Correlations need to be defined in order to avoid illogical and unrealistic combinations of the randomly selected input values, which would distort the results. This serves to ensure that differences in model outputs between scenarios can be attributed to the examined N abatement measures, and not to randomly introduced biases through the simulation. For example, a cow with the physiological potential for a relatively high milk yield in the reference case must not be compared to a cow with a relatively low potential in the scenario. Due to large data sets available, specific mutual correlations could be determined between the prices of the feed inputs barley, soy, rape, wheat and plant oil, as well as pig and milk prices; all correlations with a significance level of 0.01 were used. For other variables, where testable data series were unavailable, correlations were purely based on logical connections. This applied to: N excretion rates for pig and dairy (correlation between reference case and scenarios), provision costs of grass and hay and attainable milk yield (reference case and scenario). All correlations used for the simulation can be found in Table A.4 in the Annex.

3. Results

The baseline calculations drew on literature data and yielded deterministic estimates of partial gross margins and N abatement. The uncertainty analysis, by contrast, generated estimates of the probability to arrive at a particular outcome, i.e. at a given profit margin or N loss. When presented as a cumulative distribution, probabilities can be specified for a given outcome, e.g. how likely it is for a certain margin or N loss to be exceeded.

Partial gross margins (PGM). For both pig and dairy farming, the proposed N abatement measures increased PGM compared to both reference scenarios. For pigs, optimised single-phase and three-phase feeding surpassed the baseline of 1.19 €/kg meat by 3.4 and 4.2 percent, at 1.23 and 1.24 €/kg, respectively. In milk production, improved forage quality yielded a PGM of 0.28 €/kg, exceeding the baseline of 0.25 €/kg milk by 12 percent.

The cumulative probabilities of partial gross margins show that, even when allowing for considerable uncertainty in production costs and markets, the proposed abatement measures are economically preferable to the reference cases, and that farmers are highly likely to benefit from implementing them (Fig. 1). For the two pig feeding scenarios, PGM is almost identical; the probability is only 0.43 for S1_pig and 0.42 for S2_pig, respectively, that the gross margin is smaller than the baseline value of 1.19 €/kg meat. In the REF case, this probability is 0.51 (in a slightly skewed pdf with a median below the mean value). The PGM for improving dairy forage quality (S_milk) has a probability of only 0.26 to be below the baseline value of 0.25 €/kg milk; this is more likely to happen for the REF scenario, with a probability of 0.51.

These results indicate that all considered measures make economic sense. Feeding adjustments for pigs reduce the expensive protein components in the diet, which outweighs the costs of investment and additional feed components such as synthetic amino acids and plant oil. Higher milk yields of dairy cows compensate for increased feed provision costs when enhancing forage quality.

N losses. Comparing the likely N losses of the reference cases with those of the scenarios (Fig. 2) shows that the proposed feeding methods reduce N losses in most cases, and thus effectively abate N emissions (NH_3, N_2O and NO). Under all simulated production conditions, phase feeding for pigs (S2_pigs) is likely to abate more N emissions than the optimised single feed mix (S1_pig) (Fig. 2a). Higher-quality forage for dairy cows increases the total amount of N excretion and emissions per cow. These losses are however outweighed by an increase in milk yields, thereby increasing overall nitrogen-efficiency (Fig. 2b).

[Insert Fig 1 here]

[Insert Fig 2 here]

Abatement costs (AC) are negative under nearly all simulated production conditions (Table 3 and Fig. 3). For both pig scenarios, the probability of a negative AC is close to 1. In other words, the chance that an individual farmer is burdened with actual costs when implementing the measures is 0.1% in S2_pig, and even less in S1_pig. Both AC distributions have a similar degree of dispersion, and are between -52 and +4 €/kg N, for S1_pig and between -35 and +5 €/kg N for S2_pig (Table 3). Thus, while S1_pig offers a slight economic advantage, S2_pig is more effective at reducing N losses (see above). Investment costs do not play a decisive role here. They range from 0.52 €/pig in the baseline calculation (based on initial investments of € 7500) to a maximum of 2.09 €/pig (based on an investment of 30,000 €). The maximum investment would still only reduce the PGM from 1.24 to 1.22 €/kg meat, considering a depreciation time of 15 years.

For milk production, the situation is even more evident as the Monte Carlo analysis shows no cases with abatement costs above 0, and the AC probability distribution is less strongly dispersed than the respective distributions of the pig measures. Thus, it is very likely that the implementation of the measures is beneficial for each individual farmer. Abatement costs are of the same order of magnitude as for the pig measures (mean -21 €/kg N, Table 3). The economic feasibility of the dairy measure clearly depends on the increase in milk yield that is required to offset both the additional feeding costs and the additional N excretion per cow. With an average milk yield increase of 463 kg/cow/year (min 197, max 866, SD 113), the same gross margin per cow as in the reference can be maintained.

At first sight, S1_pig might seem preferable to S2_pig, due to its higher cost savings per kg N abated. However, it is also important to consider absolute differences at farm level, as is demonstrated by the baseline calculations: S1_pig generates roughly 5000 € of additional gross margin and abates 250 kg N, whereas S2_pig generates an additional 6600 € and abates 440 kg N. A farmer aiming to maximise profits would opt for S2_pig, which offers both more economic benefits and more N abatement.

As NH_3 abatement accounts for the largest share (95% of N abated), NH_3-N abatement costs almost correspond to AC_total. Conversely, although N_2O and NO abatement appears extremely beneficial for farmers in this way of presentation, it has to be considered that the total amount of avoided emissions is small.

[Insert Table 3 here]

[Insert Fig 3 here]

4. Discussion

Our results clearly demonstrate that measures to increase the N use efficiency of livestock production can simultaneously confer both economic and environmental benefit. Even without consideration of environmental benefits, the economic benefits presented here provide a reliable incentive for farmers to implement the measures. The link between these objectives, and the obvious incentive to minimise N losses, is the economic value of N in animal nutrition. At the farm level, this is reflected in negative average N abatement costs for the proposed N-efficient feeding methods (mean values of -21.2 €/kg N abated for S1_pig, -13.6 for S2_pig, -21.0 for S_milk); adopting these methods would reliably increase farmers' margins, even in the face of considerable uncertainties in production costs and product markets. Although the existence of negative abatement costs (i.e., “win-win” situations) for certain measures is well known, adoption rates are not always as high as would be expected (Glenk et al. 2014; MacLeod et al. 2010). We discuss this in more detail below.

Our estimates of economic gains are higher than those by Bittman et al. (2014) who estimated NH_3 abatement costs of low-protein feeding strategies between -2 and +2 € per kg

NH_3-N saved. However, due to large differences in costs and emissions, both between European countries and between animal categories, that estimate remains fairly rough – especially as the authors did not define a specific reference situation. Rößler et al. (2012) calculated abatement costs for pig feeding measures in Germany in a range of -11.4 to -16.5 € per kg NH_3-N saved, depending on the reference case and size of the farm, which is close to the results presented here (values have been converted from €/kg NH_3 to €/kg NH_3-N by multiplying by a factor of 17/14). Van Vuuren et al. (2015) estimated changes in pig production costs between -2.4 and +7.3 € per kg NH_3-N reduced, and costs of up to +75.3 € per kg NH_3-N when not supplementing synthetic amino acids. The authors found that, similar to pigs, low-N feeding strategies for dairy cows may induce net benefits or costs (abatement costs of -1.70 to +7.3 € per kg NH_3-N) (van Vuuren et al. 2015). However, in contrast to the present study, those studies only accounted for ammonia abatement. While NH_3 contributes the largest share of gaseous agricultural N emissions, N_2O and NO emissions from manure management and soils should also be considered for a more complete analysis. The data from such assessments can then also be used to identify trade-offs and synergies between mitigating N pollution and climate change. For instance, increasing milk yields has not only been recognised as an effective measure to abate N but also to reduce methane emissions from dairy production (Yan et al. 2010).

Sensitivities. In modelling N abatement costs, algorithms govern the effect of a given uncertainty in the input parameters on the uncertainty of the corresponding outputs. When interpreting simulation results, the following characteristics determine the influence of an input term to the overall outputs: (i) for multiplicative terms, input uncertainty is directly transferred to the output, such that factors with larger uncertainty contribute to overall uncertainty directly depending on their relative magnitude (i.e., in %). With most input factors having been assigned similar uncertainty factors (see Table A.3) these influences are similar for most parameters. In the algorithms used in this study, terms are mostly linked up by multiplication. (ii) Abatement cost calculation compares results of a given scenario with that of the reference case. Both elements are derived using a very similar approach and identical inputs, so that a differentiation of contributing factors is not possible. (iii) As investment costs per pig are small, their uncertainty does not markedly affect the results. Similarly, the uncertainties of meat/milk prices are much smaller than those of prices for feed ingredients and mixtures, and thus of lower importance for the uncertainty of results. In consequence, the uncertainties in feed prices and N excretion (implemented as multiplicative terms) have the greatest effect on the overall output uncertainties. Due to the importance of correlation between the individual input parameters, it is not possible to further differentiate these parameters and their specific impact on the overall results.

Economic rationale and decision-making. A set of assumptions has been used to construct specific measures and simulate the financial and environmental effects of their implementation. The assumption here was that farmers will make a “yes or no”-decision based on whether the proposed measure is economically beneficial for their operation. Other approaches (such as linear programming or nonlinear optimisation) mostly come from economics and aim to maximise profitability or return of capital by optimising production parameters under given constraints and market conditions (Morel et al. 2012; Niemi et al. 2010). Economic risks related to market price fluctuations and uncertainties might help explain why (risk-averse) farmers hesitate to implement measures which follow this rationale (Finneran et al. 2012). It is therefore important to look beyond purely economic factors and realise that farmers act in a complex socio-ecological system: Although they need to maintain their farms’ profitability and thus adopt an economic rationale to some extent, farms are more than just businesses; their production possibilities, and their actual production and income are highly dependent on natural resources, geographic location, weather and climate, and they face many risks and variabilities. Furthermore, besides food production, agriculture fulfils multiple functions and responsibilities, such as the maintenance of cultural landscape, biodiversity and ecosystem functions (Rossing et al. 2007). In this sense, Feola and Binder (2010) emphasise the need to consider the complex, multi-scale and multi-level nature of agricultural systems when formulating pertinent concepts and integrative models. Achieving economic objectives is most likely not the farmers' only motivation and cause for action, as is shown by sometimes low adoption rates despite negative abatement costs for certain measures (Glenk et al. 2014). This points to the existence of non-financial barriers and motivating factors that drive farmers' behaviour, such as age, education and experience of the farmers as well as social aspects including attitudes and perceptions, social norms and context, imitation of others, or role models (Barnes and Toma 2011; Feola and Binder 2010; Glenk et al. 2014). Furthermore, consumer demand or farm specific constraints such as the suitability and availability of surrounding land, labour constraints or access to technology can play a role (Glenk et al. 2014). A growing body of literature examines such behavioural aspects of decision-making processes, in several cases applying agent-based modelling (Feola and Binder 2010; Reise et al. 2012; Skevas et al. 2012). Nevertheless, economic viability and profitability of N abatement measures, as assessed in the present study, appear as important starting points. They are necessary for developing sustainable emission reduction strategies, but probably insufficient as sole incentive for farmers to take action and adopt new (feeding) practices. Further research into farmers' decision-making and perception of N reduction measures will thus be indispensable to enhance implementation.

5. Conclusion

Integrating economic and environmental aspects, we assessed the potential of three different animal feeding measures to make livestock farming more N-efficient – two measures for fattening pigs, and one for dairy cattle. Results show that those measures are economically beneficial for farmers and at the same time effectively reduce N losses to the environment. Optimised single-phase feeding and three-phase feeding for pigs reduce expensive protein components in the diet, which outweighs the costs connected with the two measures. Improving the quality of dairy forage distinctly increases milk yields and thereby compensates for increased N excretion and forage provision costs. The dairy measure and the optimised single-phase feeding for pigs can be adopted by farmers without needing to commit to long-term investment costs. As N loss is lower and partial gross margins higher for all cases for the three-phase feeding for pigs, extension services and policy should advise those farmers who know that their farming operation will be continued to invest in this technology. This is particularly relevant when the farmer is already planning to add or modify pig housing, as feeding equipment could be installed more cheaply in conjunction with other construction measures.

A Monte Carlo uncertainty analysis revealed that the generally positive conclusion not only holds for a point-estimate based on specific assumptions, but is also robust to possible market fluctuations, different physiological conditions of the livestock and variability in emission factors. Thus, the results are not limited to one specific single case based on static assumptions. The simulation results further confirm the effectiveness and wide applicability of the proposed N abatement measures, despite production conditions placing some restrictions on the choices available. By investigating measures related to both pig and dairy production in one study, we illustrated that N abatement costs (or, in this case, abatement benefits) can be comparable between husbandry systems. This also clearly shows that there is scope for simultaneous action in several fields. The approach used in this study can be applied to a range of situations, where the feasibility and effectiveness of implementing proposed measures in agriculture needs to be assessed, and communicated. Enhancing the adoption of these measures, however, will require more insights into farmers' decision-making behaviour and potential non-financial barriers to implementation as a prerequisite to develop specific policies. In the further debate on this topic, closer attention should be paid to specific background conditions under which farmers operate, such as the EU Common Agricultural Policy (CAP) and related grants and subsidies. Those policy instruments can provide further leverage for the introduction of agricultural measures and help bridge the science-policy gap, even in cases where measures are not *per se* profitable under current market conditions, but desired and valued politically. Ultimately, evidence-based guidance for individual farms needs to be part of a broader strategy to minimise external costs and to maximise environmental benefits for society as a whole.

Annex

[Insert Table A.1 here]

[Insert Table A.2 here]

[Insert Table A.3 here]

[Insert Table A.4 here]

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Tables

Table 1: Pig phase feeding – Scenario assumptions

Pigs: phase feeding	**Reference scenario (REF_pig)**	**Scenario 1 (S1_pig)**	**Scenario 2 (S2_pig)**
	Single-phase feeding	Optimised single-phase feeding	3-phase feeding
Feed components [kg/fattening pig]			
Barley	63.5	127	127
Soybean meal 44% XP	50.8	40.64	31.07
Wheat	132.08	78.232	88.84
Minerals	7.62	5.08	4.74
Plant oil	0	2.54	1.83
L-Lysine HCL	0	0.508	0.508
Total [kg/fattening pig]	254	254	254
Average crude protein content [%]	19.0%	17.7%	16.6%
Additional investment [€] (depreciated over 15 years)	-	-	7500
Slaughter weight [kg/fattening pig]	96		
Fattening places per farm	450		
Turnover rate	2.67		
N excretion [kg N/fattening pig]	3.86	3.29	2.85
Sources	Feed components: AWI 2015 (REF); Roth et al. 2011 (S1, S2) Protein contents: Dämmgen et al. 2011 Other production traits: AWI 2015 N excretion: Umweltbundesamt 2014b (REF), calc. (S1, S2)		

Table 2: Dairy cattle forage quality – Scenario assumptions

Dairy: forage quality	**Reference scenario (REF_milk)**		**Scenario (S_milk)**	
Forage quality	Medium		High	
Forage	Intake [dt DM/cow/year]	Quality [MJ NEL/kg DM]	Intake [dt DM/cow/year]	Quality [MJ NEL/kg DM]
Grass-silage	26.1	5.9	35.6	6.3
Maize-silage	8.0	6.7	11.0	6.7
Hay	6.0	5.2	8.2	5.5
Concentrate feed	intake [kg DM/cow/year]	quality [MJ NEL/kg DM]	intake [kg DM/cow/year]	quality [MJ NEL/kg DM]
Barley	452.6	8.07	452.6	8.07
Soybean meal	302.95	8.60	302.95	8.60
Rapeseed meal	302.95	7.20	302.95	7.20
Dairy compound feed	452.6	8.05	452.6	8.05
Total energy intake [MJ NEL/cow/year]	35 991		46 355	
Milk yield total [kg/cow/year]	6491		9632	
Milk for calves [kg/cow/year]	300		300	
Milk yield available for sale [kg/cow/year]	6191		9332	
N excretion [kg N/animal*year]	98.82		119.74	
Sources	Feed intake: FarmClim (Moser et al 2013), AWI 2015 Feed quality: AWI 2015; Hörtenhuber et al. 2010; DLG 2015, Resch 2007 Milk yield: calculated based on AWI 2015 N excretion: calc. based on Gruber et al. 1999			

Table 3: Abatement costs of the analysed measures.

	Pig		**Milk**
	S1	**S2**	**S**
Total abatement cost (AC_total)			
Baseline value [€/kg N abated]	-20.05	-15.08	-18.17
Stochastic simulation [€/kg N abated]			
Mean	-21.16	-13.56	-21.01
Minimum	-51.64	-35.01	-40.17
Maximum	4.30	4.91	-11.45
Standard deviation (SD)	6.72	4.90	3.56
NH_3-N abatement cost (AC_NH_3)			
Baseline value [€/kg NH_3-N abated]	-21.13	-15.89	-19.09
Stochastic simulation [€/kg NH_3-N abated]			
Mean	-22.58	-14.47	-22.26
Minimum	-55.23	-37.39	-43.63
Maximum	4.55	5.32	-12.13
Standard deviation (SD)	7.21	5.26	3.85
N_2O-N abatement cost (AC_ N_2O)			
Baseline value [€/kg N_2O-N abated]	-673.15	-506.24	-661.83
Stochastic simulation [€/kg N_2O-N abated]]			
Mean	-597.96	-383.05	-701.21
Minimum	-1863.33	-1360.43	-1863.29
Maximum	144.42	126.68	-279.64
Standard deviation (SD)	235.18	165.47	206.56
NO-N abatement cost (AC_NO)			
Baseline value [€/kg NO-N abated]	-927.44	-697.47	-895.16
Stochastic simulation [€/kg NO-N abated]			
Mean	-910.07	-582.99	-958.79
Minimum	-3081.34	-2167.51	-2619.88
Maximum	166.44	131.81	-379.83
Standard deviation (SD)	388.62	269.97	301.94

Table A.1: N excretion fattening pigs in the EU28 (Source: UNFCCC 2014, Eurostat 2014)

	N excretion [kg N/pig/year]	**Slaughter weight [kg/pig]**
Ireland	6.68	97.50
France	6.95	90.69
Denmark (KP)	8.01	94.89
Netherlands	8.58	89.41
Sweden	9.21	96.84
Spain	9.34	79.95
Austria	9.48	91.58
Portugal	9.48	83.29
Hungary	9.57	87.11
Belgium	9.90	90.74
Latvia	10.00	82.29
Estonia	10.24	93.58
UK	10.41	68.53
Lithuania	10.71	98.01
Luxembourg	11.21	82.42
Germany	11.29	124.48
Bulgaria	11.94	104.40
Slovenia	12.19	75.31
average EU-28	**12.03**	**92.12**
Italy	12.54	83.11
Poland	13.56	93.26
Cyprus	16.00	93.42
Greece	16.00	70.80
Slovakia	16.27	112.24
Finland	17.45	109.90
Romania	17.73	129.77
Croatia	20.00	82.84
Czech Republic	20.00	92.24
Malta	-	80.88

Table A.2: N excretion and milk yield of dairy cows in the EU28 (Source: UNFCCC 2014)

	N excretion [kg N/cow/year]	milk yield [kg/cow/year]
Romania	53.63	3650
Latvia	70.00	5249
Poland	86.70	4993
Ireland	99.71	5183
Bulgaria	99.89	4263
Croatia	100.00	3424
Cyprus	100.00	6330
Slovakia	100.00	6293
Austria	100.26	6418
Hungary	100.38	7128
Lithuania	101.18	5227
Greece	102.63	5752
Luxembourg	107.89	7260
Average EU-28	**108.07**	**6538**
Spain	110.21	7818
Slovenia	111.22	5592
France	115.16	6767
Italy	116.00	6428
Germany	116.85	7278
Portugal	117.30	8176
Estonia	118.09	7526
Belgium	118.12	7507
Netherlands	122.30	8192
UK	122.56	7446
Sweden	124.22	8724
Finland	129.81	8114
Czech Republic	135.78	7413
Denmark (KP)	138.03	8373
Malta	-	-

Table A.3: Triangular probability distribution functions of uncertain parameters. (Mode values used for baseline calculation)

Stochastic variable	Minimum	Mode	Maximum	Determination of minimum & maximum	Source
Prices					
Pork [€/kg]	1.3	1.66	2.3	calc.	Statistics Austria 2014
Milk [€/kg]	0.31	0.37	0.48	calc.	
Barley [€/kg]	0.09	0.12	0.24	calc.	
Wheat [€/kg]	0.09	0.12	0.25	calc.	
Soybean meal [€/kg]	0.2	0.3	0.5	calc.	
Rapeseed meal [€/kg]	0.18	0.27	0.51	calc.	
Dairy compound feed [€/kg]	0.2	0.3	0.5	Assumption: same as soy	
Plant oil [€/kg]	0.6	1.2	1.8	50%	Landesbetrieb Landwirtschaft Hessen 2012
L-Lysine HCL [€/kg]	1	2	3	50%	
Minerals [€/kg]	0.4425	0.885	1.3275	50%	AWI 2015
Grass silage REF [€/dt DM]	4.48	8.95	17.90	Factor 2	
Grass silage S [€/dt DM]	4.69	9.37	18.74	Factor 2	
Hay REF [€/dt DM]	4.91	9.81	19.62	Factor 2	
Hay S [€/dt DM]	5.22	10.43	20.86	Factor 2	
Maize silage [€/dt DM]	4.39	8.78	17.56	Factor 2	
Investment cost phase feeding [€]	6500	7500	30 000		ALB Hessen 2008
Milk yield REF_milk [kg/cow*year]	5263	6191	7120	15%	Calc. based on energy intake (AWI 2015)
Milk yield S_milk [kg/cow*year]	7932	9332	10 732	15%	
N excretion REF_pig [kg N/fattening pig]	3.28	3.86	4.44	15%	Umweltbundesamt 2014b
N excretion S1_pig [kg N/fattening pig]	2.80	3.29	3.79	15%	Calc. based on N_ex pig REF and protein content of feed
N excretion S2_pig [kg N/fattening pig]	2.43	2.85	3.28	15%	
N excretion REF_milk [kg N/animal*year]	79.05	98.82	118.58	20%	Calc. based on Gruber et al. 1999, Spiekers et al. 2015
N excretion S_milk [kg N/animal*year]	95.79	119.74	143.69	20%	
Emission factors (EF)					
EF animal housing NH_3 [kg NH_3-N/kg Nex]					European Environment Agency (EEA) 2013, IPCC 2006b, 2006a; Umweltbundesamt 2014a, 2014b; Winiwarter and Rypdal 2001
Pig	0.09	0.15	0.21	40%	
Dairy	0.07	0.12	0.17	40%	
EF manure storage NH_3 [kg NH_3-N / kg TAN]					
Pig	0.07	0.12	0.17	40%	
Dairy	0.09	0.15	0.21	40%	
EF manure management N_2O [kg N_2O-N / kg Nex]	0.0005	0.001	0.002	Factor 2	
EF total from manure management NO [kg NO/year*AAP]					
Pig	0.0005	0.001	0.002	Factor 2	
Dairy	0.0035	0.007	0.014	Factor 2	
EF broadcast spreading liquid manure [kg NH_3-N / kg TAN]					

Pig	0.15	0.25	0.35	40%	
Dairy	0.3	0.5	0.7	40%	
EF manure spreading NO [kg NO-N/kg N in manure]	0.005	0.01	0.02	Factor 2	
EF direct emissions from soils N_2O [t N_2O-N/tN applied]	0.00625	0.0125	0.025	Factor 2	

Table A.4: Correlations used for Monte Carlo simulation

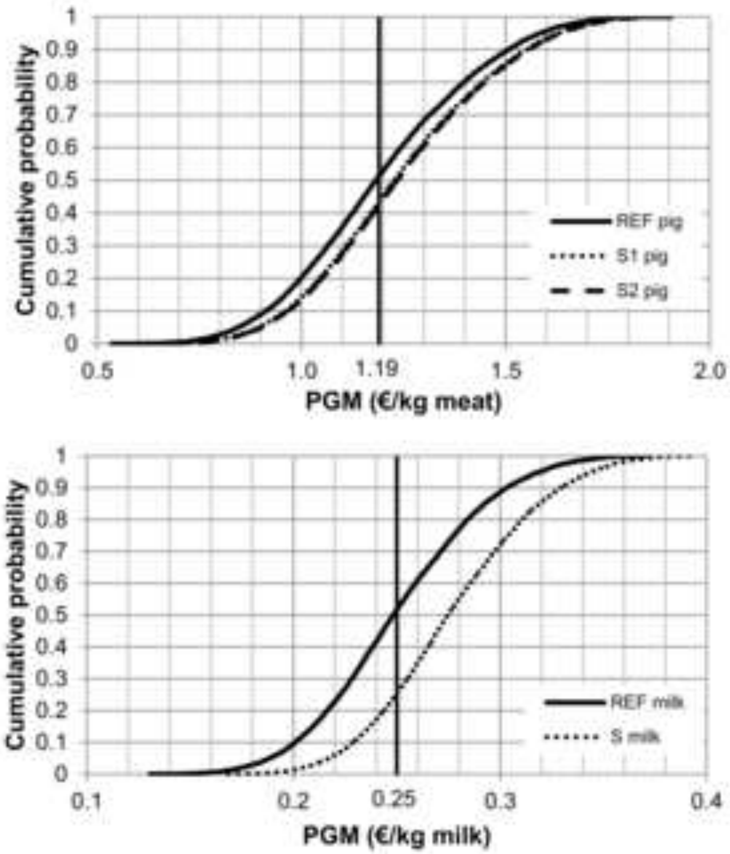
Prices					
	Barley	Soy	Wheat	Plantoil & rape	Milk
Barley	1				
Soy	0.288	1			
Wheat	0.899	0.419	1		
Plantoil & rape	0.668	0.639	0.71	1	
Milk	0.366	-	-	-	1
Forage provision cost					
	Grass REF_milk	Grass S_milk	Hay REF_milk	Hay S_milk	
Grass REF_milk	1				
Grass S_milk	1	1			
Hay REF_milk	1	1	1		
Hay S_milk	1	1	1	1	
Milk yields					
	Milk yield REF_milk	Milk yield S_milk			
Milk yield REF_milk	1				
Milk yield S_milk	1	1			
N excretion					
	N_ex REF_pig	N_ex S1_pig	N_ex S2_pig	N_ex REF_milk	N_ex S_milk
N_ex REF_pig	1				
N_ex S1_pig	1	1			
N_ex S2_pig	1	1	1		
N_ex REF_milk	-	-	-	1	
N_ex S_milk	-	-	-	1	1

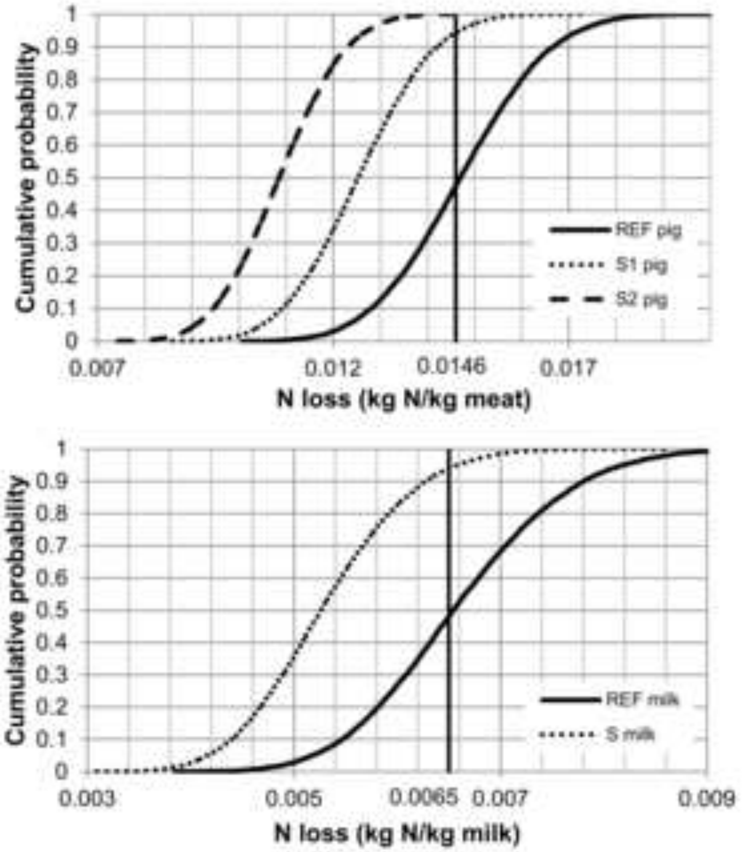
Figure captions

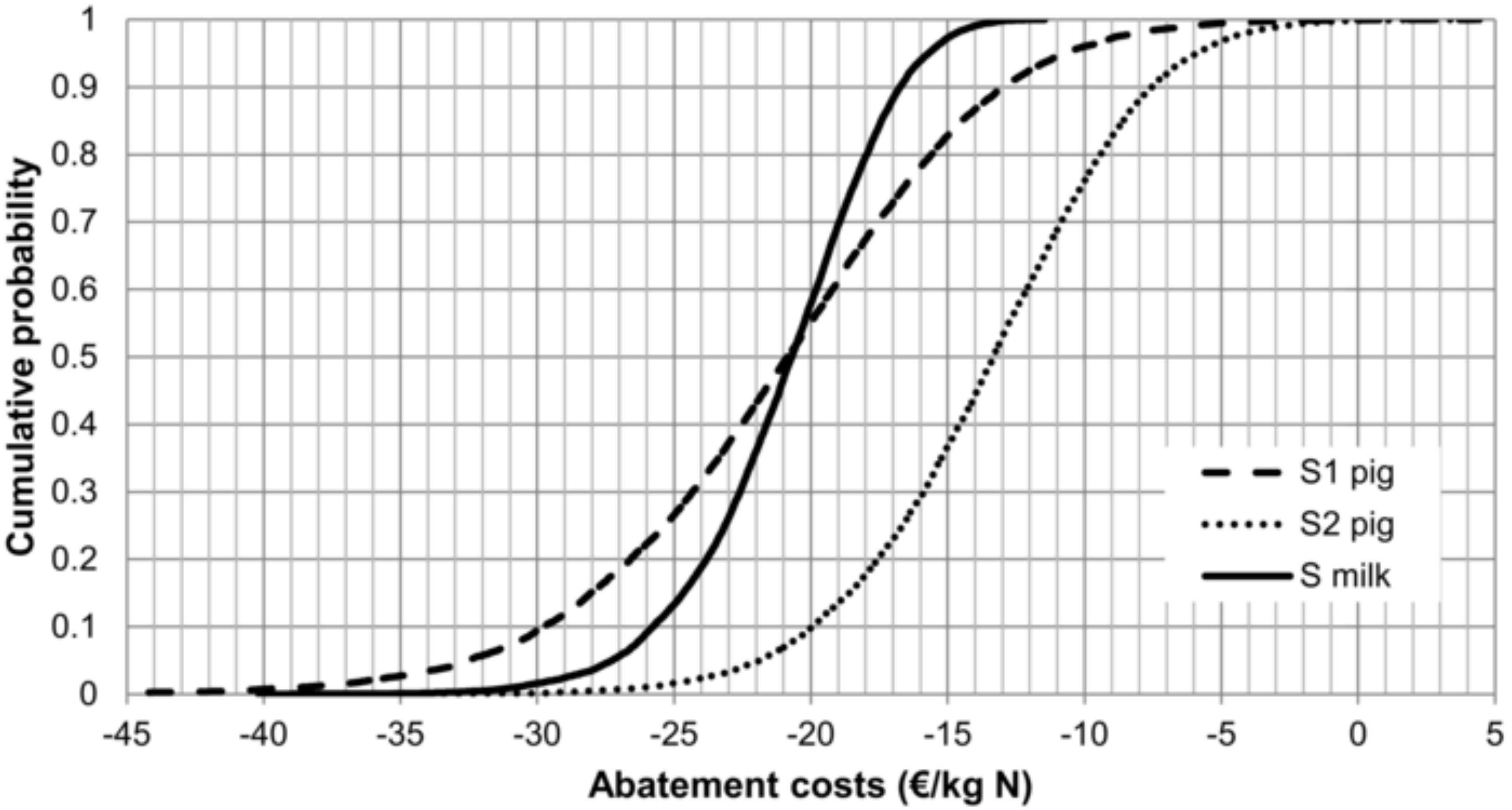
Fig. 1 Cumulative probabilities of partial gross margins. **a)** pig (€/kg meat). Solid line: REF_pig, dotted line: S1_pig, dashed line: S2_pig; **b)** dairy (€/kg milk). Solid line: REF_milk, dotted line: S_milk. The vertical line in both a and b marks the baseline value from REF (considering no uncertainties)

Fig. 2 Cumulative probabilities of N losses, including NH_3, N_2O and NO. **a)** pig (kg N/kg meat). Solid line: REF_pig, dotted line: S1_pig, dashed line: S2_pig; **b)** dairy (kg N/kg milk). Solid line: REF_milk, dotted line: S_milk. The vertical line in both a and b marks the baseline value from REF (considering no uncertainties)

Fig. 3 Cumulative probabilities of abatement costs for all analysed measures (€/kg N). Dashed line: S1_pig, dotted line: S2_pig, solid line: S_milk


Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1.0
1.19
1.5
2.0
PGM (€/kg meat)
REF pig
S1 pig
S2 pig
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.25
0.3
0.4
PGM (€/kg milk)
REF milk
S milk


Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.007
0.012
0.0146
0.017
N loss (kg N/kg meat)
REF pig
S1 pig
S2 pig
Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.003
0.005
0.0065
0.007
0.009
N loss (kg N/kg milk)
REF milk
S milk


Cumulative probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-45
-40
-35
-30
-25
-20
-15
-10
-5
0
5
Abatement costs (€/kg N)
S1 pig
S2 pig
S milk