Economics of GHG abatement strategies in Finnish mixed dairy farms

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Abstract:

We develop a theoretical framework to analyse economically optimal GHG abatement strategies for a mixed farming system with crop and dairy production. Subsequently, it is implemented as a detailed bio-economic optimization model for mixed arable-dairy farms with non-linear crop and milk yield functions and a detailed accounting of Green House Gas emissions, and parameterized to Finnish agricultural and environmental conditions. Focusing on the role of sunk costs of investments and opportunity costs of labour, we analyse optimal farm management decisions under different CO2 tax levels, considering adjustments at the extensive and intensive margin, including changes in manure storage systems and application methods. We find that the amount of GHG abatement responds more strongly to the level of sunk and opportunity costs than the CO2 tax level which underlines the relevance of the planning horizon for that type of analysis. Our findings reveal that low cost abatement options in dairy production are limited. Our model can be easily adjusted to other locations, market and policy conditions and thus provides an interesting starting point for international comparisons.

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JEL Codes: Q52, Q54

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Key words: carbon tax, greenhouse gas emissions, bio-economic modelling, sunk costs

JEL codes: Q58, Q54, Q18

1. Background and introduction

In colder climate, grassland production systems focusing on dairy and feed production dominate not only economics in farming, but also environmental externalities including Green House Gas (GHG) emissions, the latter mainly due to methane emissions from enteric fermentation of ruminants. Any serious attempts to reduce GHGs from farming under these conditions therefore will have to focus on ruminant based farming systems. On-farm GHG abatement strategies either work along the extensive margins – reducing herd sizes and managed agricultural land – or the intensive one, by changing farm managing practises such as nitrogen fertilization, animal diets or manure handling.

In European context non-CO_2 GHG emission reductions and abatement costs for European agriculture has been studied by De Cara et al. (2005) by employing a farm-type, supply-side oriented, linear-programming model of the European agriculture. Also Pérez Domínguez et al. (2003) estimate marginal abatement cost curves for EU Member States by employing the CAPRI (Common Agricultural Policy Regional Impact Analysis) modelling system, which is a large-scale comparative-static agricultural sector model.

This paper develops a simple theoretical framework for a mixed farming system with crop production and dairy production. The theoretical model is then applied empirically by employing a detailed bio-economic model to analyse the interactions of GHG abatement strategies in mixed dairy farms in Finland. Besides adjusting the crop land allocation, the herd size, the feed mix and mineral fertiliser and manure application levels, the model also considers technological switches regarding manure storage (from non-covered to covered manure storage) and manure spreading (from broadcast spreading to injection) as GHG abatement options. Also manure N excretion response to dietary changes is modelled in following.

While there is vast body of literature analysing the interaction between yields, fertilization and climate change relevant emissions based on bio-physical models (cf. Britz and Leip 2009), application of non-linear yield functions in more complex farm-scale bio-economic models is, however, still scarce. For example, Lengers et al. (2014) use a purely linear model in their analysis which considers similar abatement options as we do, but do not consider yield response or non-linear substitution between concentrates and fodder, focusing on different GHG emission indicators. Similarly, De Cara et al. (2005) use more aggregate linear single farm models in their European wide analysis, however fixing crop and milk yields.

Furthermore, and also underlined by Lengers et al. (2014), the abatement costs predicted by different models hinge strongly on assumed costs and output prices. Our focus in this paper is especially on the role of sunk costs. These are especially relevant in dairy farming which is characterized by long-lasting investments in stables and the milking parlour which account for a larger part of total production cost. Equally important for the flexibility of farming systems to more structural changes is the role of opportunity cost of labour. Our analysis aims to shed light on the impact of sunk costs of investment and opportunity costs of labour on GHG abatement strategies and costs in mixed farming systems.

The underlying economic assumptions, especially regarding opportunity costs of land and labour, turn out to be crucial in our analysis for key results and subsequent policy conclusions. Our findings underline the usefulness of detailed bio-economic analysis to inform the policy debate regarding the role of agriculture and especially ruminants based production systems in GHG abatement.

The paper is organized as follows. Section 2 develops a theoretical framework for mixed farming system. In section 3 the building blocks of bio-economic optimisation model are presented. Section 4 provides first results regarding the baseline situation without CO_2 taxation and then the impact of different CO_2 taxation levels on farm management and GHG abatement is presented. Section 5 concludes.

2. Theoretical framework for a mixed farming system with crop production and dairy production

In what follows we develop a simple but powerful model of dairy farm. The main production line of the farm is thus milk production with grazing with a supporting line of arable crop cultivation which mainly produces fodder, but can also produce cash crops. The key decision choices relate to herd size and milk yield. Thus, in the theoretical framework, we assume that these are determined first and crop production is adjusted accordingly. Also, we assume that the dairy farm has enough own land to ensure silage production and manure spreading while keeping open a possibility for manure exports outside the farm. Note that the empirical model discussed in section 3 will consider all choices simultaneously.

2.1 Dairy production

Consider a dairy farm with H lactating cows. Denote the price of milk by p^M and let the price of concentrates be p^v. The main inputs in milk production are silage (s) and concentrate (v) as feedstocks which jointly determine milk yield per cow: $Q = g(s, v)$. In practice, the farmer decides the amount of concentrate feeding and the animals have free access to silage. That voluntary silage intake per cow is described by a total intake function, $\gamma(v)$ with $\gamma'(v) > 0$ and $\gamma''(v) < 0$. Given the intake function, milk yield per cow can be expressed simply as Q = g(v) with g$'(v) > 0$ and g"$(v) < 0$. Animal upkeep related costs and profits from exported animals are assumed constant per milking cow, and denoted by φ. A function $I(H)$ describes costs of investing in production facilities, machinery and animal shelters, depending on the size of the herd. The farm's total land area is denoted by A and costs of manure exports from the farm by a cost function C. Manure produced per cow, denoted by w, tend to increase with higher concentrate feeding. The total net profit from milk production is,

$$\pi^M = [p^M g(v) - v\, p^v + \varphi]H - I(H) - C[w(v)H - mA]. \qquad (1)$$

The first part in brackets describes the net profit per cow: revenues per cow – i.e. milk price times milk yield -, minus concentrate costs and other costs including fodder production, minus investment costs and costs for manure handling.

The dairy farmers chooses the diet and determines the size of the herd according to

$$\pi_v^M = [p^M g'(v) - p^v]H - C'w'(v)H = 0 \qquad (2a)$$

$$\pi_H^M = [p^M g(v) - v\, p^v + \varphi] - I'(H) - C'w(v) = 0, \qquad (2b)$$

Note first the optimality condition of concentrate (2a) is independent of the size of the herd, reflecting the maximal available silage. Omitting first the marginal impacts on manure handling, the optimal concentrate use per cow equates the value of the marginal product of the milk yield with the concentrate price. As concentrate feeding tends to increase manure per cow and potential costs of exporting manure out of the farm, the optimal amount of concentrate feeding is marginally reduced depending on these cost.

The second-order conditions for the optimum hold, so the first-order conditions implicitly determine the optimal concentrate diet v* and the optimal size of herd H* from (2b). For the given v* and H*, the intake function determines the required amount of silage: $X = (g(v^*) - v^*)H^*$. This impacts crop allocation and management, not detailed in here, but reflecting in the empirical part. Furthermore, optimal herd size and milk yield also determine the amount of manure produced as $M = w(v^*)H^*$, which needs to be spread either in the farm or exported from it.

2.2 Silage and crop production

To facilitate the analysis of crop allocation and intensity, we make some simplifying assumptions. Firstly, all farm facilities are located at the centre of the farm. The farmer produces silage and possibly cereals by choosing the appropriate amounts of manure and mineral fertilizer application. As silage has relatively high transportation costs compared to cereals, it tends to be produced in field parcels close to the farm centre. To keep the model simple, we assume that manure spreading costs increase in the land area it is applied. Let a denote the spreading costs of manure, then $a = a(A)$ with $a'(A) > 0$ and $a"(A > 0)$. In contrast, the price of mineral fertilizer, p^l is constant and its application cost is insignificant. Silage has no off-farm market value and thus its profitability is defined by the production and opportunity costs, p^s. Cereals, in contrast, can be sold at a unit price of p^c. Both crops are produced by using a fertilizer input. The dairy farm may apply both manure and mineral fertilizer. Mineral fertilizer applied per hectare is denoted by l, and the manure applied per hectare by m. By assumption both nutrient inputs are perfect substitutes in crop production. The response function of the crops in terms of nitrogen applied either in the form of mineral fertilizer or in manure, respectively, is as follows,

$$y^i = f^i(N), \text{ with } f_N^i > 0 \text{ and } f_{NN}^i < 0, \tag{3}$$

from which one has by differentiation $y_l^i = \varepsilon f_N^i$ and $y_m^i = \theta f_N^i$. Here ε denotes the N content of mineral fertilizer and θ the N content of manure.

The net profits from the farmland cultivation can be expressed as follows:

$$\pi^A = [p^s f^s(\varepsilon l_s + \theta m) - p^l l_s - a(A)m]\beta A + [p^c f^c(\varepsilon l_c + \theta m) - p^l l_c - a(A)m)](1-\beta)A \tag{4a}$$

The first part denotes net profits from producing silage on a share β of the land, the second part net profits from cereals on the remaining area.

The farmer's cultivation decision is constrained by the fact that silage use and manure application cannot exceed the amounts actually produced. Thus, we require that

$$\begin{gathered}[(f^s(\varepsilon l_s + \theta m)]\beta A - [\gamma(v^*) - v^*]H^* \geq 0 \\ w(v^*)H^* - mA \geq 0\end{gathered} \tag{4b}$$

The constrained maximization problem (3)–(4) describes farmer's cultivation choices. The Lagrangian function can be expressed as follows:

$$L^A = [p^s f^s(\varepsilon l_s + \theta m) - p^l l_s - a(A)m]\beta A + [p^c f^c(\varepsilon l_s + \theta m) - p^l l_c - a(A)m)](1-\beta)A$$
$$+\mu_1[f^s(\varepsilon l_s + \theta m)]\beta A - [\gamma(v^*) - v^*]H^* + \mu_2(w(v^*)H^* - mA) \tag{5}$$

The farmer chooses the use of fertilizers and land allocation. Starting with silage, the farmer may use either manure or mineral fertilizer according to

$$L_m^A = [p^s f_N^s \theta - a(A)]\beta A + \mu_1 f_N^s \theta \beta A = 0 \tag{6a}$$

$$L_l^A = [(p^s f_N^s \varepsilon - p^l]\beta A + \mu_1 f_N^s \varepsilon \beta A = 0 \tag{6b}$$

Similar fertilization choice is made for land area devoted to cereal crop production but note that this an unconstrained choice

$$L_m^A = [p^c f_N^c \theta - a(A)](1-\beta)A = 0 \qquad (7a)$$

$$L_l^A = [(p^c f_N^c \varepsilon - p^l](1-\beta)A = 0 \qquad (7b)$$

Finally, the farmer allocates land between silage and cereal crops according to

$$L_\beta^A = [p^s f^s(\varepsilon l_s + \theta m) - p^l l_s - a(A)m]A - [p^c f^c(\varepsilon l_c + \theta m) - p^l l_c - a(A)m)]A$$

$$+\mu_1[f^s(\varepsilon l_s + \theta m)]A = 0 \qquad (8)$$

We start our interpretation with equation (6a) and (6b). Both equations indicate that per unit of land, fertilization is chosen by equating the value of marginal product augmented by the shadow value of the silage target to respective costs.

The next issue is to decide which field parcels are fertilized using manure and which ones with mineral fertilizer; only the lowest cost form of fertilization is used. For both equation sets (6a)-(6b) and (7a)-(7b) we obtain the following indifference relation:

$$\frac{a(A)}{\theta} = \frac{p^l}{\varepsilon} \qquad (9)$$

By equation (9) manure is spread in areas close to farm centre and expanded thereafter up to the point where expanding manure spreading area is less profitable than applying mineral fertilizer in those field parcels.

By equation (8) land allocation is made according to a condition:

$$[(p^s + \mu_1)f^s(\varepsilon l_S + \theta m) - p^l l_s - a(A)m] = [p^c f^c(\varepsilon l_c + \theta m) - p^l l_c - a(A)m)] \qquad (10)$$

Thus, the profits from both production lines should be equal when the requirement of silage is taken into account by its shadow price.

2.3 Dairy production and policy instruments

Suppose now that authorities introduce climate policies and design optimal policy by levying the first-best Pigouvian tax on all sources of CO_2-eq emissions, thus chosen to be equal to the societal value of abating one unit of CO_2 to prevent further Global Warming.

The highest share of GHG relevant emissions from milk production stem from methane emissions due to enteric fermentation by the herd. Expressed as CO_2-equivalents, these emissions per cow can be denoted by $e^c = e^c(v)$. A second important source are N_2O and CH_4 emissions from manure storage, which can be defined per cow as $\varphi w(v)$, yielding jointly:

$$\left(e^c(v) + \varphi w(v)\right)H \qquad (11)$$

Assuming that CO_2 equivalent emissions linked to the use of intermediate inputs and investment goods are already levied on the industries producing them, further relevant sources of emissions are background emissions from soil as well as emissions from mineral fertilizer application and manure spreading. Background soil emissions, denoted with μ per hectare, are constant on the whole land area A so that the overall soil emissions are μA. Emissions from mineral fertilizer per hectare are denoted by γl and emissions from manure spreading are σm. Accounting for the land allocation gives the emissions from cultivating silage and cereal crops as,

$$\mu A + [\gamma l_s + \sigma m(A)]\beta A + [\gamma l_c + \sigma m(A)](1-\beta)\mu A \qquad (12)$$

Let t denote the tax on emissions. Then the economic problem of milk production under the first-best Pigouvian carbon tax is

$$\pi^M = \left[p^M g(v) - v\,p^v + \varphi - t\left(e^c(v) + \varphi w(v)\right)\right]H - I(H) - C[w(v)H - mA]. \ (13)$$

The dairy farmers chooses the diet and determines the size of the heard according to

$$\pi_v^M = \left[p^M g'^{(v)} - \ p^v - t\left(e^{c\prime}(v) + \varphi w'(v)\right)\right]H - C'w'(v)H = 0 \quad (14a)$$

$$\pi_H^M = \Phi - \mathrm{t}\left(e^c(v) + \varphi w(v)\right) - I'(H) - C'w(v) = 0 \qquad (14b)$$

Compared to the optimality condition without the tax (1) above, the carbon tax reduces the revenue per cow which tends to reduce concentrate feeding. A similar impact is found in the choice of the size of the herd. Revenue obtained from each cow is reduced, and so is the optimal size of the herd.

Consider next how a hypothetical animal carbon tax impacts the choices of the dairy farm. Suppose that the tax is levied on average CO_2-equivalent emissions (over all dairy farms) from enteric fermentation, manure storage and manure excreted on pasture land per productive animal. Denote this figure of average emissions by $\tilde{e}$. Thus, the animal carbon tax payment per cow is $t\tilde{e}$ and the total tax payments is given by $t\tilde{e}H$. As the tax base is a constant average, the tax is simply a lump-sum carbon tax. Thus, in our model this tax impacts only the size of the heard leaving cultivation qualitatively the same as before.

The profit from milk production under the animal carbon tax is

$$\pi^M = [p^M g(v) - v\,p^v + \varphi - t\bar{e}]H - I(H) - C[w(v)H - mA]. \ (15)$$

The dairy farmers chooses the diet and determines the size of the heard according to

$$\pi_v^M = \left[p^M g'^{(v)} - \ p^v\right]H - C'w'(v)H = 0 \qquad (16a)$$

$$\pi_H^M = \Phi - \mathrm{t}\bar{\mathrm{e}} - I'(H) - C'w(v) = 0 \qquad (16b)$$

By equation (16a), the choice of the diet is qualitatively the same as in the private optimum. The choice of the heard, however, differs, as the lump-sum tax is levied on each cow. Thus, the number of cows will decrease.

3. Bio-economic model of mixed farming system

We use a Non-Linear programming approach to implement the theoretical model above which quantifies the bio-economic processes discussed above and simulates optimal related decision making of a farmer. Crop yields are endogenously depicted by N-dependent yield functions of either the Mitcherlich or quadratic functional form, the different crops including silage compete for arable land, while pasture land per cow is fixed. The model either maximizes profits or utility when production risks for crops are considered. Different assumptions with regards to opportunity costs of labour and the share of fixed costs considered are analysed in the following as important drivers of the chosen abatement strategies. We drive abatement by charging taxes on CO_2 equivalent emissions related to the decision variables of the farmer. Compared to other bio-economic models, especially the non-linear yield functions and the endogenous use of IPCC Tier 3 emission accounting is worth to be mentioned. Technically, the model is implemented in GAMS and solved by CONOPT. A model documentation detailing all equations and parameters are provided in technical annexes (Annex 1 and 2). We discuss in the following only the main components relevant to understand the subsequent discussion of the results.

3.1. Feed intake and milk yield functions

The total feed intake function of dairy cows [kg Dry matter/animal/year] is quantified based on Huhtanen et al. (2008) as:

$$intake(v) = (v - 0.163v - 0.0188v^2 + 13.4) * 365 \quad (17)$$

In the intake function v denotes concentrate feed intake, such that silage intake in dry matter is given by *intake(v) – v*.

A quadratic milk yield function [kg/animal/year] from Lehtonen (2001) is applied

$$g(v) = (20.09 + 1.252\, v - 0.04\, v^2) * 300 \quad (18)$$

By assumption each cow has 300 milking and 60 dry days. **Figure 1** shows that milk production peaks at around 8.900 litres with concentrate intake of 16 kg on average of the 300 lactation days. Under the assumed price of concentrates of € 0.183per kg and milk price of € 0.45 per kg, the optimal level is very close to the maximum if other impacts of a higher milk yield are not taking into account. In our model, these other impacts relate to modest increases in variable costs and labour input needs per cow when milk yield increases. Still, as found in the results, farmers operate close to the maximal yields.

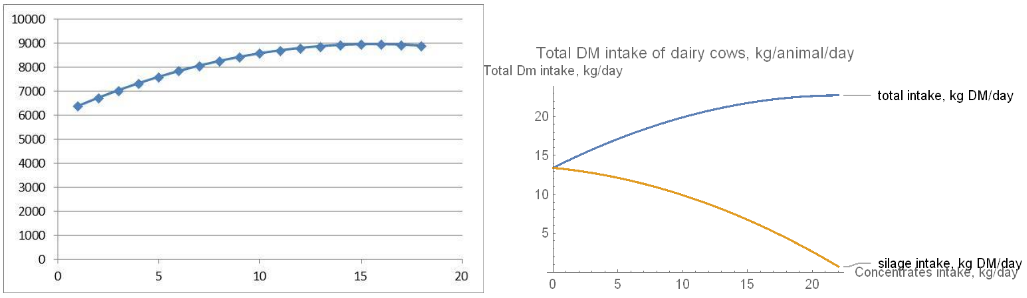

Figure 1: Milk yield in kg per year depending on daily concentrate intake and resulting intake of fodder

Total silage production in the farm is not fixed, but depends both on the chosen acreage and the silage yield which depends on N fertilization.

3.2 Crop yield functions

The crop nitrogen response function for silage (kg DM yield/ha) is given by equation (19) and for wheat by equation (20):

$$y^s(N) = a + bN + cN^2 \tag{19}$$

$$y^c(N) = \varphi(1 - \sigma \exp(-\rho N)) \tag{20}$$

where a, b and c are parameters of a quadratic nitrogen response function and φ, σ and ρ are parameters of a Mitscherlich response function. The parameters of the quadratic crop yield functions are taken from Lehtonen 2001 and those of the Mitscherlich yield function have been estimated by Bäckman *et al*. (1997) on the basis of Finnish field experiments. Both nitrogen response functions are illustrated in **Figure 2** and show the decreasing marginal product of N fertilization. The optimal point depends on the price ratio between the output price and nitrogen, for silage the implicit output price depends on the interaction with concentrates in the milk yield function discussed above. The model considers wheat, barley, rape and silage with endogenous nitrogen response function, while the productivity level of grasslands is fixed.

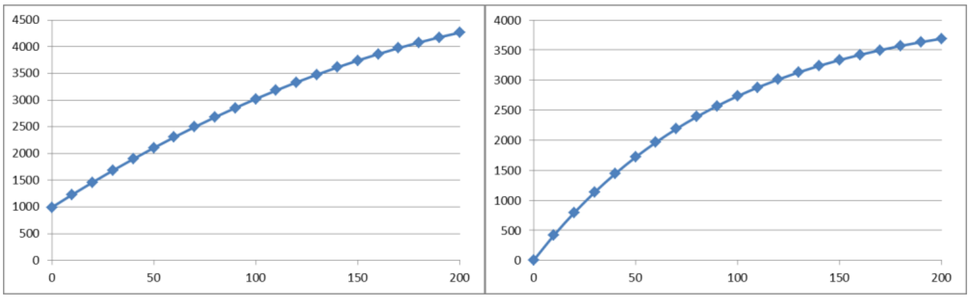

Figure 2: Quadratic N-response function for silage (left) and Mitscherlich function for wheat (right)

3.3. GHG emissions

GHG emissions account for (1) Methane from enteric fermentation and from manure storage, (2) direct N_2O emissions from storage, (3) NH_3 emissions from manure storage and spreading (and indirectly through those N_2O emissions), and (4) GHG emissions from cultivated land including autonomous soil emissions and (5) emissions from cultivation practices, crop yield transportation and grain drying, and (6) mineral fertilizer manufacture. Furthermore, we take soil carbon sequestration into account when arable land is put under green set-aside, emissions accounted by the IPCC under land use change.

Enteric fermentation is the most important source of climate change relevant greenhouse gases in dairy farming and its reaction to the milk yield and the digestibility of the cow's diet is shown in **Figure** 13.

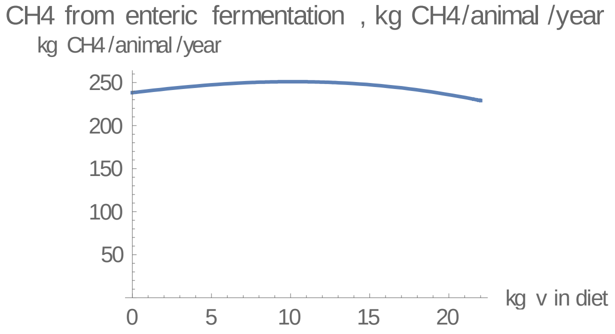

Figure 3: Methane emission from enteric fermentation from cows, depending on concentrate uptake

Manure storage is a source of both methane and nitrous dioxide emissions. **Figure 4** describes both emissions in terms of CO_2-equivalent emissions as a function of concentrate feeding under two alternative manure storage technologies: not covered manure storage and storage with floating cover. As figure 4 suggests, the technology plays the main role: a floating cover decreases emissions about 30% at all concentrate feeding levels. Feeding itself has a role if the storage is not covered.

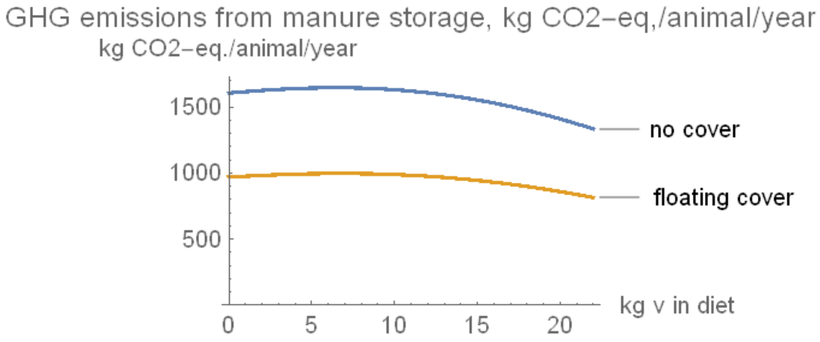

Figure 4: GHG emissions from the manure storage

4. Results

4.1 Baseline

The baseline situation is characterized by a mixed dairy farm with 60 hectares of arable land and up to 40 hectares of pasture, reflecting the EU-15 average of about 60 dairy cows (EC 2014). The pasture area is set to 60 ha, reflecting slightly higher than the EU-15 average (which is 51 ha). It is tailored to Finnish conditions using the following assumptions. The farm relies on a part-time grazing with 4 months season, thus, the diet remains unchanged also during the grazing season. Due to grazing, a part of the manure is excreted to the pasture and not to the cowshed (i.e. less manure to storage and spreading). The pasture area is 0.5 ares/dairy cow/day. The pasture area is fertilized using mineral fertilizers (220 kg N/ha) and is not harvested for silage. Cultivation costs and GHG emissions from the pasture are assumed the same as for silage. As an assumption, each dairy cow has three milking seasons before it is slaughtered. This determines the required amount of calves and heifers for replacement to keep the animal number constant. The feed intake and manure excretion of calves and heifers is assumed to be constant. Dry cows are not accounted for separately. The milking season of dairy cows is 300 days/year, and otherwise functions for feed intake and manure excretion are the same for the entire year.

Under current market and policy conditions, the farm devotes 55 hectares of the arable land to silage production and the remaining acreage to produce rape seed. All arable land receives support payments under the first and second pillar of the CAP, under the first pillar, 190 €/ha, plus 270 €/ha under the second pillar as Less Favourable Area (LFA) payments. Rape seed receives additional coupled area payments of around 50 €/ha. In total, the farm receives close to 41.000 €/year as CAP support based on non-current production. Note that LFA payments to set-aside land are however upper limited to 50% of the total farm land, a condition irrelevant for the baseline.

Due to the assumption of relative high milk prices of 0.45 €/kg, the herd of around sixty dairy cows at close to 8.900 litres milk yield per cow generates market revenues of around 270.000 € yearly. Finnish dairy production is highly labour intensive with more than 100 hours per dairy cow (including fodder production) such that the labour input totals 7.800 working hours. Important cost items are costs for concentrates close to 69.000 € and for N-fertilizer with 29.000 €. Other costs sum up to around 31.000 €.

Assuming that all labour is family labour, the profit is around 175.000 € which suggests returns to labour of 22 €/hour. However, that neglects the fact that the bulk of the 40.000 € of support payments are decoupled and do not depend on managing the farm. Note also that any fixed costs in dairy production are missing so far in the calculation. They amount to around 900 € per cow per year and would thus decrease the profit by 60.000 €. If the decoupled character of the support payments is considered and the remaining profits of around 145.000 € are decreased by the fixed costs, the decision-dependent profit of the farm amounts to 85.000 € in total or to around 11 €/hour. That implies that under even moderate opportunity costs of 13 €/hour for working off-farm, dairy production is not profitable in the long run – farm would idle the land and still receive a large share of the CAP support and would work off-farm. That finding will be highly relevant for the subsequent analysis and underlines the importance of opportunity cost for labour when analysing GHG abatement strategies and cost.

The farm emits 660 tons of CO_2 equivalents each year of which the bulk of 390 tons stems from enteric fermentation, followed by 130 tons from fertilization. About 100 tons are linked to cultivation. These numbers fit quite well to findings in other studies for intensive dairy systems in the temperate zone.

4.2 Impact of GHG taxes on farm management and emissions

In order to understand the interplay of farm management, GHG emissions and opportunity costs, we change the fixed costs share accounted for by the farmer. A share of unity implies that no costs are sunk, the decision about land use, herd size and input use intensity levels are taken jointly with the decision if and how much to invest in farm buildings and machinery. We assume that at that time, the farmer faces opportunity cost of labour of 13 €/hour reflecting that he could alternatively decide to not invest and work off-farm. The opportunity costs are relatively low as we assume that firstly, a family member involved in dairy farming works per week more than would be legally allowed when working as a hired-labour, secondly, that income taxation and social security legislation favour returns from farming, and thirdly, that the farmer would face costs for commuting.

Under full opportunity costs, as already discussed above, dairy farming is not profitable under Finnish conditions as seen below from Figure 5: the number of dairy cows is zero even if no CO_2 taxes are levied under full fixed costs accounting, implying that only above average productive farmers would fully re-invest in dairy farming. If the farmers face only sunk cost and has no opportunity to work off-farm, he would keep his herd even under extremely high taxes of 200 €/ton of CO_2 equivalent.

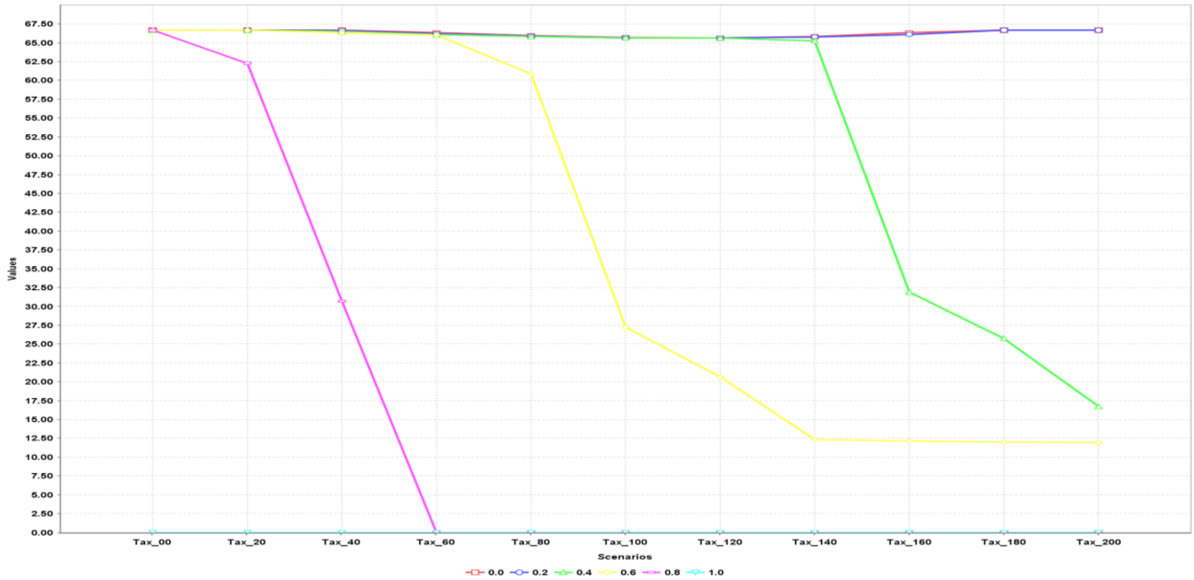

Figure 5: Dairy herd size under different CO_2 tax levels

The profit developments (see **Figure 6**) might look curious at first glance, but reflects the importance of sunk cost. If fixed costs are not accounted for as they are fully sunk and assumed to have occurred in the past, the profits of the farm are clearly highest. However, the decision space of the farmer is also limited as we assume that he cannot work off-farm, reflected in zero labour opportunity cost. The farmer would continue the dairy farm operation as long as market revenues exceed variable costs including the CO_2 taxes. As GHG abatement options are limited, the farm carries a high CO_2 tax load. Its profits under the highest assumed tax rate of 200 €/ton of CO_2 are around 75.000 €. Considering the 41.000 € of decoupled support payment, the dairy branch remunerates labour only with 4.5 €/hour.

Farmers who have to invest fully or partly in the nearer future tend to have lower (expected) profits if opportunity costs of labour follow the relative change in fixed cost. Note that saved fixed costs need not be fully offset by improved labour opportunities: the profits under 60% fixed cost share accounted for and 60%x13 €/h = 7.80 €/h opportunity cost of labour generate about the same profits as under full accounting.

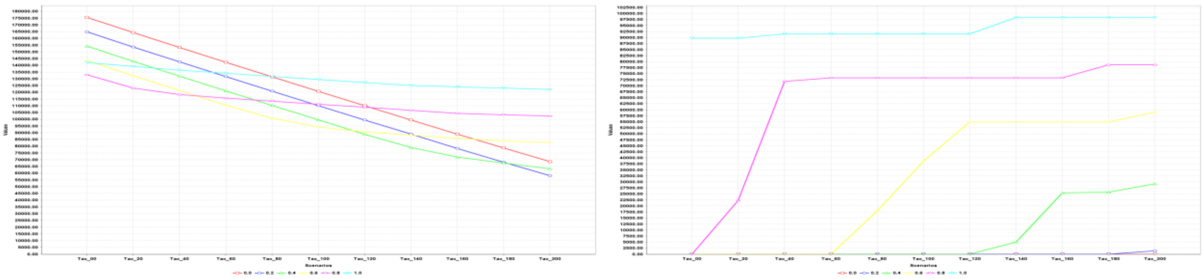

Figure 6: Profits (left) and off-farm income (right) under different CO_2-tax levels

If the farmer only continues the arable crop production (cereals and oilseeds) and does not invest in dairy farming under full fixed cost accounting (share=1.0), the biggest share of the income already in the starting situation stems from working off-farm (see **Figure 6**, right panel). That income increases further under higher CO_2 tax loads where part of the land is idled (left uncultivated). The changes in the crop allocation are depicted in **Figure 7**. Note the grassland is always idled. Rape seed remains competitive even under high tax levels as it requires little N fertilization and receives additional coupled support payment. However, its maximal rotational share is assumed with 20%. Wheat allows for the highest yield and market returns, but is also the crop with the highest N fertilization and is substituted by set-aside when a CO_2 tax is introduced. Once the total set-aside on arable and grass lands of the farm reaches 50 ha, additional hectares are not granted with LFA support and barley becomes competitive as opportunity cost of land drop. At very high tax loads, the all land besides the small area of rape seed is idled.

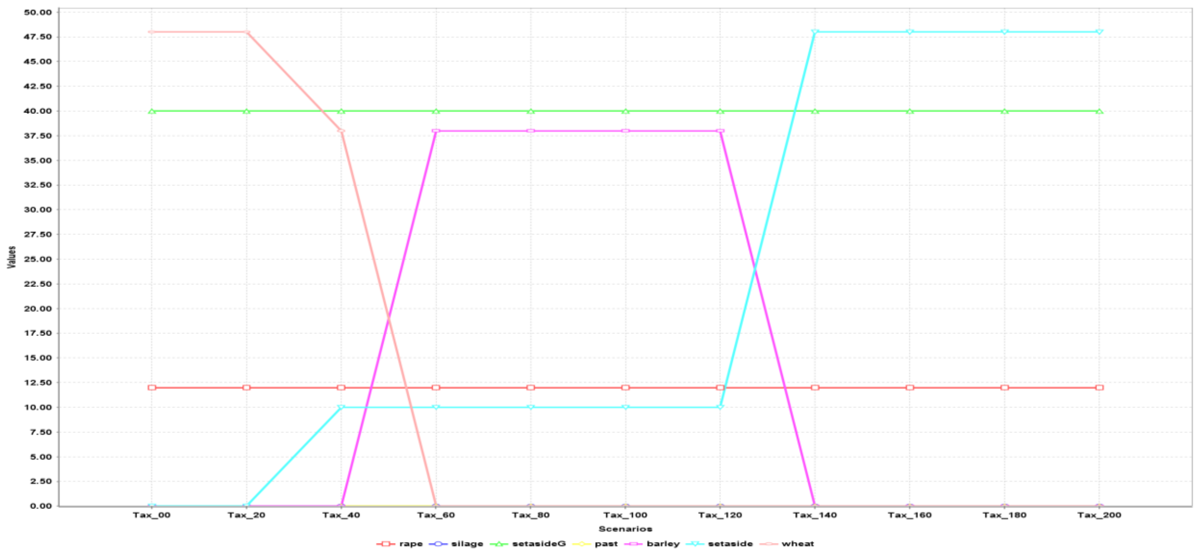

Figure 7: Changes in the crop allocation under different CO2-tax levels, arable farm

The observations from above are clearly reflected in the GHG emission levels in **Figure 8**. If the farmer keeps the dairy herd, less than 10% of total GHG emissions are reduced. If only arable farming is present and the grass land is idled, already at zero tax rates only around one third of the GHG emissions of the mixed farm are emitted. Switching from arable land to set-aside leads to higher carbon sequestration and the farm is even saving GHGs under very high CO_2 emissions taxes.

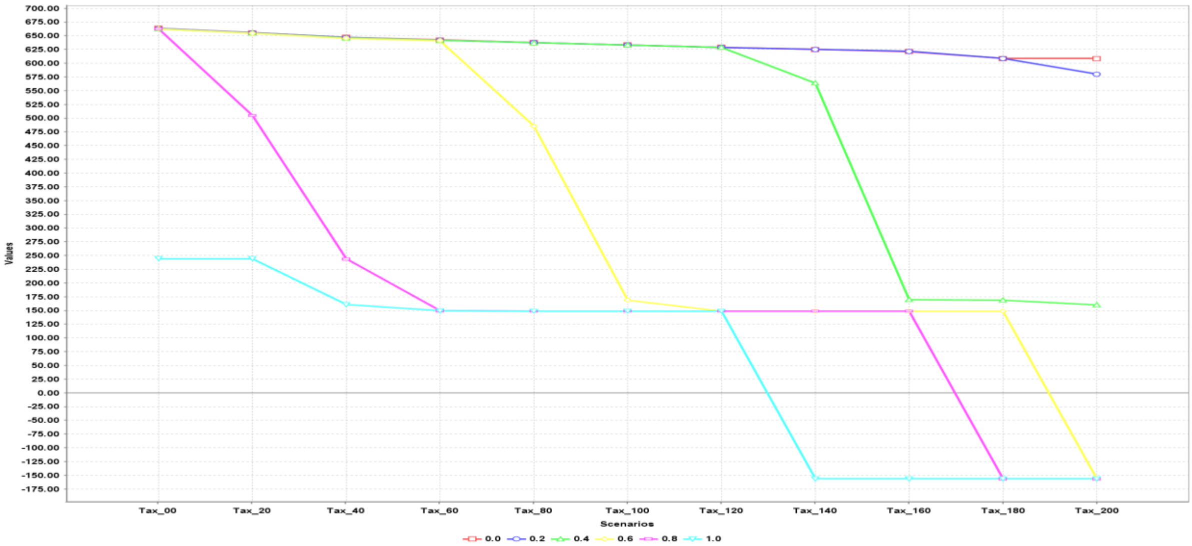

Figure 8: Total GHG emissions under different CO_2 tax levels

We will now have a closer look at the changes at the intensive margin. As seen from **Figure 9** below, milk yields and concentrate use per cow react to environmental taxes, but even the direction is depending on the opportunity costs. At low opportunity cost - 0 or 20% of fixed cost accounted for - concentrate use per cow almost doubles under the highest assumed tax rate compared to the baseline. An increased concentrate share in the diet leads to a higher digestibility of the diet which in turn reduces Methane emissions from enteric fermentation (see **Figure 10**). At the same time, the higher concentrate use allows reducing the fodder intake per cow such that total fodder production can be reduced by reducing yields (see **Figure 11**). The alternative strategy which leads to higher returns to labour is to reduce the concentrate use per cow – which leads to lower cost per cow – and to reduce the herd. It is chosen under high opportunity costs of labour. The impact on the intensity of fodder production is similar as reducing the herd clearly also decreases fodder needs. However, yields react more strongly to CO_2 taxes if the extensive strategy based on reduced herds is economically optimal, see Figure 11.

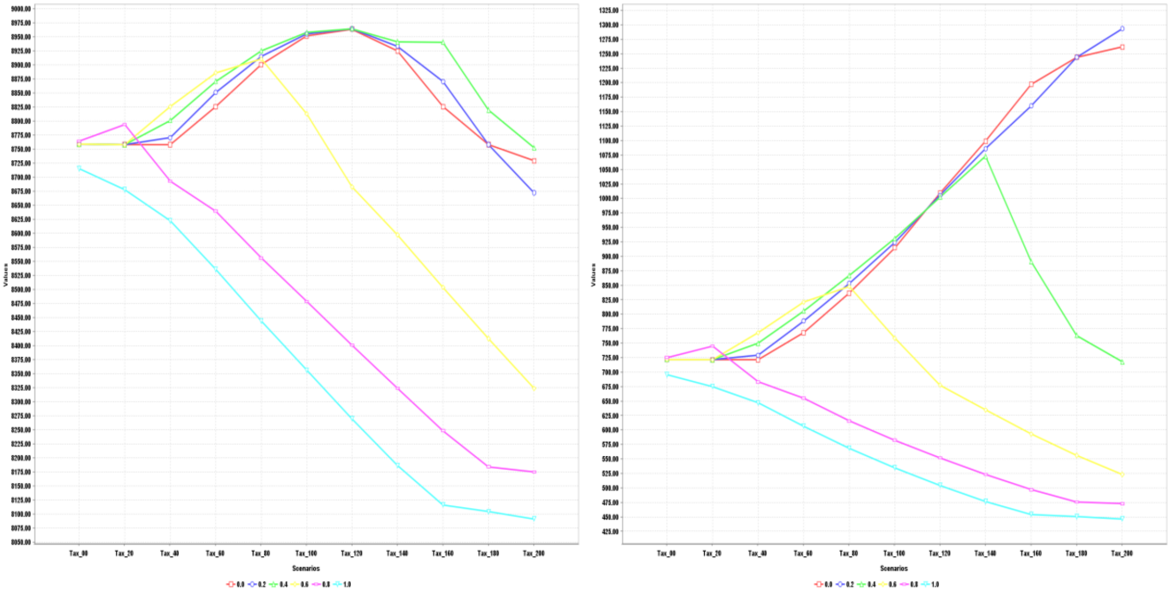

Figure 9: Milk yield (left) and concentrate use per cow (right), under different CO_2 taxes

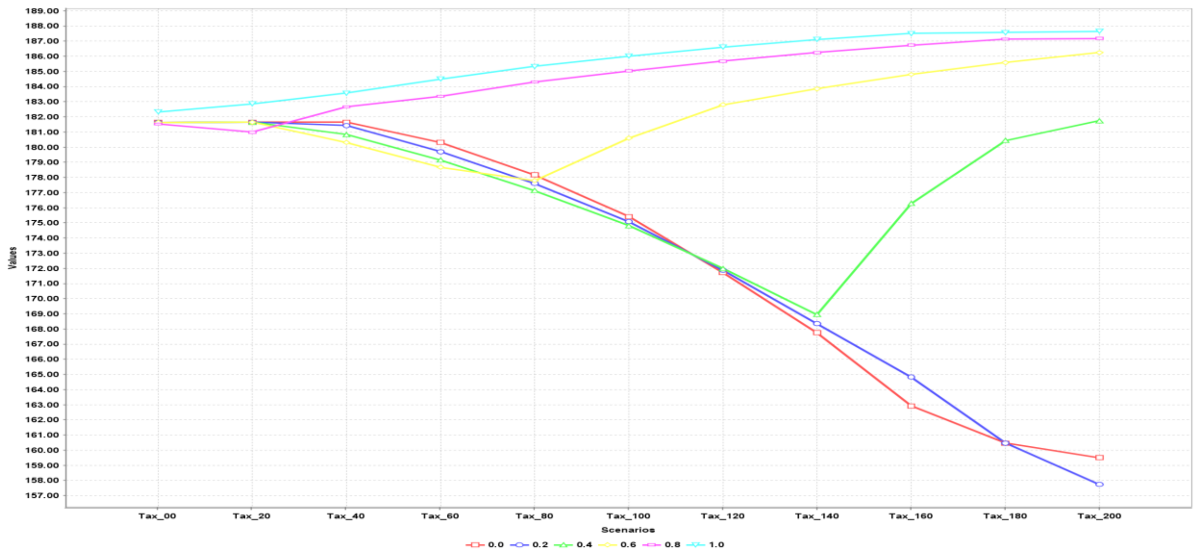

Figure 10: CH4 from enteric fermentation, under different CO_2 taxes

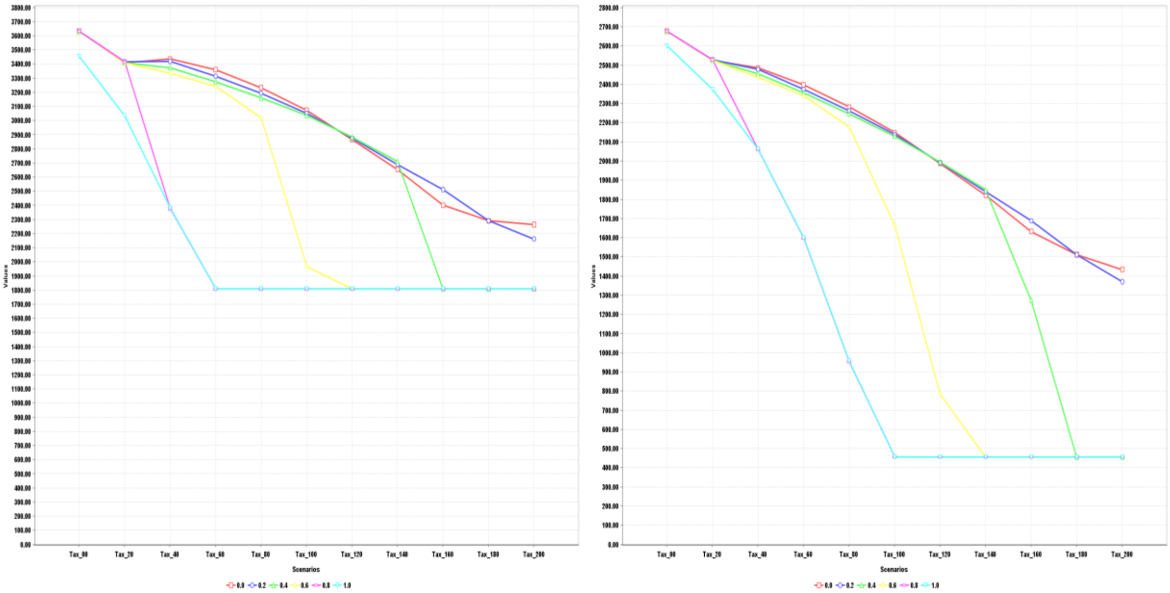

Figure 11: Management intensity of silage (left) and pasture (right), as seen from yield, under different CO_2 taxes

We will now have a closer investigation of changes at the extensive margin for the case with no opportunity cost and full sunk cost. Total GHGs savings amount to around 8 % (see **Figure 12**). As seen in Figure 12 below, despite the fact that methane emissions (mainly from enteric fermentation) account for the largest share of the GHGs, they are reduced only to a very limited degree by around 3%. The GHG savings stem from increasing the concentrate feed use per cow by almost a quarter and thus substituting silage, which increases the digestibility and thus reduces methane emissions. The GHG savings from cultivation stem from removing the around 5 ha of rape seed and increasing the land area allocated to silage. That in turn, combined with higher concentrate use, allows decreasing the silage yields by 27%. Due to the non-linearity of the yield response to N fertilization, fertilizer levels on silage drop by 47%. Overall, average N-fertilization per ha drops from around 160 kg to 65 kg in the farm such that share of mineral fertilizers are reduced from 83% to 36%. The farm also uses improved manure storage and applications methods: the manure storage is covered and land application is injected. However, for the manure coverage, the direction is not clear as it kicks in and out depending on the tax load which reflects the fact that a higher concentrate use per cow also increases N excretion per cow.

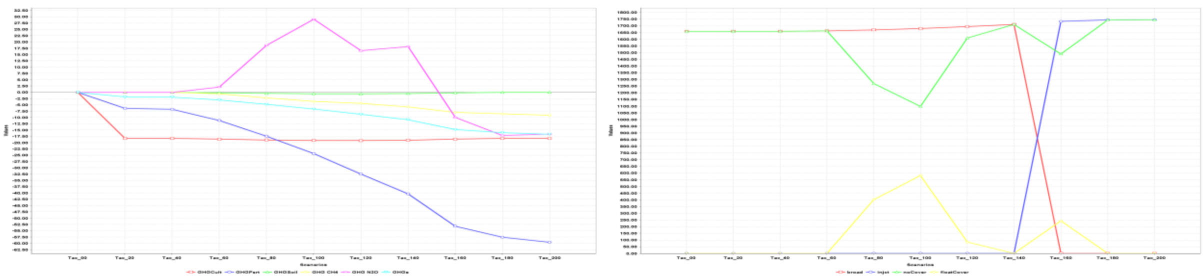

Figure 12: Percentage difference in GHG emission compartments under different CO_2 taxes (left) and manure management (right), no fixed costs

5. Conclusions

The quite different findings discussed above underline the importance of opportunity costs and the planning horizon when evaluating GHG abatement strategies and costs in mixed farming system. In the short run, investment costs are sunk and lower considerably decision-dependent costs. The impact is intensified if labour input is considered fixed or by assuming low or zero opportunity costs.

Our findings support results from other studies which underline rather high abatement costs in dairy farming at least when some remarkable GHG emission reduction is targeted (cf. Lengers et al. 2014). We also confirm that reducing milk yields is not an economically viable option. That relates to the facts that reduced milk yields will distribute the GHG emissions related to maintenance, growth and activity of the herd over a reduced output quantity while the lower digestibility of fodder will negatively impact methane emissions, both driving up GHGs per kg of milk produced.

Overall, our findings confirm that it is far from easy to balance the benefits from using grasslands to produce milk and meat against the resulting climate change impacts. However, changes at the extensive margin, i.e. from result milk output, are hard to judge about in a supply-side model as it is unclear how markets would react to reduced supply in a regulated region. If demand is inelastic, follow-up price increases could trigger production elsewhere and simply shift GHG emissions (emissions leakage) from one region to another one. That implies that the type of detailed analysis at farm level presented in here must be implemented for major producing regions and linked with global-scale market analysis.

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Annex 1. Key equations of the empirical model

Manure excretion to cowshed, m^3/animal/year

To determine the manure excretion one needs to define the following shares of animals in the farm. A notion of *production animal* refers to the steady-state process needed to maintain one lactating cow and is technically a composition of one lactating cow, 1/3 calf and 1/3 heifer. Thus, define

$$shareD = 1,\ shareH = \frac{1}{slaught},\ shareC = \frac{1}{slaught}$$

where $slaught$ is the number of milking seasons before a dairy cow is slaughtered, and the ending D stands for dairy cows, H for heifers and C for calves. Using this notation, the manure excretion to cowshed and pasture, respectively, can be defined as follows ((Nennich et al. 2005):

Manure excretion to cowshed, m^3/production animal/year

$$w(v) = \frac{[(intake(v)*w1+w0)\ shareD+wC*shareC+wH*shareH](1-wp)365\ scale}{1000} + h2o$$

Manure excretion to pasture, m^3/ production animal/year

$$wpa(v) = \frac{[(intake(v)*w1+w0)\ shareD+wC*shareC+wH*shareH]wp\ 365\ scale}{1000}$$

Manure N content

To determine the manure N content, one needs to account for the share of manure N evaporated as NH_3-N. This evaporation is affected by manure storage and spreading technologies and defined as $ammonia^{ij} = emstor^i * emsperad^j$, where $i = \{1,2\} = \{no\ cover, floating\ cover\}$ and $j = \{1,2\} = \{broadcast, injection\}$. Manure N content, kg N/m^3 manure/year (ThetaN) and total N excretion in manure, kg N/animal/year (Nexcr), respectively, are based on Nennich et al. (2005) and given by

$$ThetaN(v) = \frac{(1-ammonia^{ij})\ scale\left(intake(v)\left(\frac{v}{intake(v)}*vcp+\left(1-\frac{v}{intake(v)}\right)scp\right)N1+BWD*N2\right)365}{(w(v)+wpa(v))1000}$$

$$Nexcr(v) = \frac{(1-ammonia^{ij})\ scale\left(intake(v)\left(\frac{v}{intake(v)}*vcp+\left(1-\frac{v}{intake(v)}\right)scp\right)N1+BWD*N2\right)365}{1000}$$

Manure transport and application cost

Costs for manure spreading and transportation are determined based on the distance, amount of manure, spreading technology, gear capacity and contractor charge as follows.

$$em(r,m) = \frac{m}{spcap}\left(\frac{2*r}{trsp} + load * spcap + \frac{spread^i}{60} * spcap\right) * spp^i + ctran * r * m$$

where $i = \{1, 2\} = \{broadcast, injection\}$, m is m^3/manure and r is distance in km.

CH_4 emissions from enteric fermentation

Methane emissions are calculated applying a procedure from GHG inventory calculations that follow IPCC's recommendations. Calculation is based on the following set of equations that are based on the inventory reporting of the Statistics Finland (2016). When estimating CH_4 emissions from enteric fermentation, the diet's gross energy digestibility is calculated only for dairy cows, and the same value is used for calves and heifers for simplification. The same set of equations are thus used for calculating the emissions for dairy cows, heifers and calves. Dry cows are not accounted for separately.

$EFem(v) = \frac{(GED(v)*shareD+GEH(v)*shareH+GEC(v)*shareC)*Ym*365}{55.65} * \frac{(100-fatinc*4)}{100}$, where

$GEX(v) = \frac{\frac{NEmX+NEaX+NE1(v)+NEpX}{REM(v)} + \frac{NEgX}{REG(v)}}{DE(v)/100}$

$REM(v) = 1.123 - \left(4.092 * 10^{-3} * DE(v)\right) + (1.126 * 10^{-5} * DE(v)^2) - \frac{25.4}{DE(v)}$

$REV(v) = 1.164 - \left(5.160 * 10^{-3} * DE(v)\right) + (1.308 * 10^{-5} * DE(v)^2) - \frac{37.4}{DE(v)}$

$NEgX = 22.02 * \frac{BWX}{(CoX*MW)^{0.75}} * WGX^{1.097}$

$NEpD = CpD * NEmD$ (only for dairy cows)

$NE1(v) = \frac{g(v)}{300} * (1.47 + 0.40 * fat)$ (only for dairy cows)

$NEaX = \left(cap * \frac{tpX}{365} + cao * \left(1 - \frac{tpX}{365}\right)\right) * NEmX$

$NEmX = CfiX * BWX^{0.75}$

$DE(V) = -11.3 + 0.977 * \frac{seosoas(v)}{10}$, where $seosoas(v)$ is the share of digestible organic matter of the total organic matter as g/kg DM

$X = \{D, H, C\}$

GHG emissions from manure storage

Manure storage is a source of both methane and nitrous dioxide emissions. They are defined using the following equations:

CH_4 emissions from storage, kg CH_4/animal/year (based on Statistics Finland 2016)

$EFmm(v) = \left(GED(v) * \left(1 - \frac{DE(v)}{100}\right) + 0.04\right) * \left(\frac{1-ash}{18.45}\right) * 365 * chmax * 0.67 * mcf^i$

where mcf^1 is storage without cover and mcf^2 is storage with floating cover

Direct N_2O emissions from storage, kg N_2O/animal/year (based on Statistics Finland 2016)

$EFmn(v) = \frac{Nexcr(v)*wp}{(1-ammonia^{ij})} * ef^i * \frac{44}{28}$

where ef^1 is storage without cover and ef^2 is storage with floating cover

GHG emissions from manure management

Manure storage and spreading cause NH_3 emissions and based on those indirectly N_2O emissions. Drawing on Statistics Finland (2016) and Grönroos (2015) they can be expressed using the following equations.

NH_3 emissions from manure management, kg NH_3-N/m^3 manure/year

$$ThetaNvol(v) = \frac{ThetaN(v)}{(1-ammonia^{ij})} * ammonia^{ij}$$

Indirect N_2O emissions from manure managements, kg N_2O/m^3 manure/year

$$EFmni(v) = ThetaNvol(v) * 0.01 * \frac{44}{28} + ThetaN(v) * 0.01 * \frac{44}{28}$$

Emissions from fertilizer use, machinery and soil (kg CO_2-eq./ha) from cultivated land

The GHG emissions from cultivated land comprise autonomous soil emissions (soil N_2O emissions due to fertilization are assumed to be included here, i.e. they are not accounted for separately) and emissions from cultivation practices, yield transportation to processing, crop drying and manufacturing mineral fertilizers.

$$ghgX(N) = autoX + cultX + emtrans + emdry * y^X(N) + emprod * N$$

where X is {s, c}={silage, barley}

Emissions from fertilizer use, machinery and soil (kg CO_2-eq./ha) from pasture land

The GHG emissions from pasture land are calculated based on Statistics Finland (2016) with additional terms for autonomous soil emissions, cultivation practices and mineral fertilizer manufacture.

$$empas(v,H) = \left(H * wpa(v) * \frac{\frac{\frac{Nexcr(v)}{wpa(v)}}{1000}}{(1-ammonia^{ij})} \right) * 0.02 * \frac{44}{28} * N2O + (autop + cultp + emprod * lp)Ap(H)$$

Annex 2: List of parameter values

Parameter	Symbol	Value	Reference
Market price, €/kg			
Milk	p^M	0.4455	OSF (2014)
Concentrate, domestic	p^v	0.183	Tuottopehtori (2014)
Concentrate, soybean meal	p^{soy}	0.3507	IndexMundi (2014)
Mineral fertilizer, YaraMila Y2	p^l	0.45	Tuottopehtori (2014)
Meat	p^{meat}	2.1	Tuottopehtori (2014)
Calf (selling), €/animal	p^{calf}	115	Tuottopehtori (2014)
Mineral fertilizer, YaraMila Y2			
N-content	ε^N	0.24	Tuottopehtori (2014)
P-content	ε^P	0.04	Tuottopehtori (2014)
Variable cost in barley production, €/kg	h^C	0.056	Tuottopehtori (2011)
Variable costs in silage production			
€/kg yield	$h0$	0.0918	Tuottopehtori (2014)
Silage dry matter %	$dmpc$	25	
Silage density, kg/m^3	$dens$	250	
Loading capacity, m^3	$trcap$	20	
Transport speed, km/h	$trsp$	15	
Transport price, €/h	trp	63.1	Palva (2015)
Cost of floating storage cover, €/m^2/year	$float$	2	
Capacity of manure spreader, m^3	$spcap$	16	Palva (2015)
Contractor charge for spreading, €/h			
Broadcast spreading	spp^1	77.9	Palva (2015)
Injection	spp^2	102.5	Palva (2015)
Time for loading, h/m^3	$load$	0.004	
Time for spreading, min/m^3			
Broadcast spreading	$spread^1$	0.5	
Injection	$spread^2$	1.5	
Transport cost interrelated to spreading, €/m^3/km	$ctran$	0.4	Palva (2015)
Damage from GHG emissions, €/kg CO_2-eq.	ζ^G	0.05	
Animal body weight, kg			
Dairy cow	BWD	600	
Heifer	BWH	400	VTT (2000)
Calf	BWC	150	VTT (2000)
Number of milking seasons	$slaught$	3	
Number of dairy cows	H	60	chosen
Share of animals per dairy cow			
Dairy cow	$shareD$	1	
Heifer	$shareH$	1/3	
Calf	$shareC$	1/3	
Total intake, kg DM/animal/day			
Heifer	inH	5	
Calf	inC	10	
Share of concentrates in H and C diet, %		50	
Manure excretion, m^3/animal/year			
Heifer	wH	8.5	Finlex 1250/2014
Calf	wC	6.25	Finlex 1250/2014
Water in liquid manure, m^3/animal/year	h2o	10	
Manure density, kg/m^3	kgm3	1000	
Share of manure excreted on pasture	wp	0.15	
Scaling factor to match Finnish statistics	$scale$	0.65	chosen
Parameter for manure excretion	$w0$	9.4	Nennich et al. (2005)

Parameter for manure excretion	$w1$	2.63	Nennich et al. (2005)
Parameter for manure N content	$N1$	84.1	Nennich et al. (2005)
Parameter for manure N content	$N2$	0.196	Nennich et al. (2005)
Feed nutrition values			
Concentrate (barley 54-62 kg/hl)	v		
Dry matter, g/kg	cka	860	
Organic matter, g/kg DM	coa	971	
Organic matter digestibility	$coas$	0.82	
Crude protein content of DM	vcp	0.126	
P content of DM	vp	0.0041	
Concentrate (soybean meal)	v		
Dry matter, g/kg	cka	880	
Organic matter, g/kg DM	coa	821	
Organic matter digestibility	$coas$	0.88	
Crude protein content of DM	vcp	0.520	
P content of DM	vp	0.007	
Silage feed (grass silage)	s		
Dry matter, g/kg	ska	1000	
Organic matter, g/kg DM	soa	911	
Organic matter digestibility	$soas$	0.74	
Crude protein content of DM	scp	0.161	
P content of DM	sp	0.0031	

Parameters for nitrogen response functions	Symbol	Value	Reference
Quadratic response function for silage	a	1182.9	Bäckman et al. (1997) and Lehtonen (2001)
	b	24.24	
	c	-0.0394	
Quadratic response function for rape seed	a	890.0	
	b	9.95	
	c	-0.0354	
Mitscherlich response function for wheat	φ	4956	
	σ	0.7624	
	ρ	0.011	
Mitscherlich response function for barley	φ	5218	
	σ	0.8280	
	ρ	0.017	

Parameters for GHG emissions	Symbol	Value	Reference
Conversion factors			
N_2O to CO_2-eq.	N_2O	298	
CH_4 to CO_2-eq.	CH_4	21	
Enteric fermentation			
Coefficients			
Dairy cow	$CfiD$	0.379	Statistics Finland (2016)
Heifer	$CfiH$	0.322	Statistics Finland (2016)
Calf	$CfiC$	0.322	Statistics Finland (2016)
Pasture	cap	0.17	Statistics Finland (2016)
Stall	cao	0.00	Statistics Finland (2016)
Pregnancy (dairy cows)	CpD	0.10	Statistics Finland (2016)

Growth			
Dairy cow	CoD	0.00	Statistics Finland (2016)
Heifer	CoH	0.80	Statistics Finland (2016)
Calf	CoC	1.00	Statistics Finland (2016)
Average weight gain, kg/day			
Dairy cow	WGD	0.05	Statistics Finland (2016)
Heifer	WGH	0.45	Statistics Finland (2016)
Calf	WGC	0.90	Statistics Finland (2016)
Pasture season, days			
Dairy cow	tpD	125	OSF (2010)
Heifer	tpH	135	OSF (2010)
Calf	tpC	115	OSF (2010)
Milk fat content, %	fat	4.3	Statistics Finland (2016)
CH_4 conversion rate	Ym	0.065	Statistics Finland (2016)
Manure storage			
No cover			
Emission factor N_2O	$ef1$	0	Statistics Finland (2016)
Emission factor CH_4	$mcf1$	0.17	Statistics Finland (2016)
Manure N evaporated as NH_3, %	$emstor1$	10	Grönroos (2014)
Floating cover			
Emission factor N_2O	$ef2$	0.005	Statistics Finland (2016)
Emission factor CH_4	$mcf2$	0.10	Statistics Finland (2016)
Manure N evaporated as NH_3, %	$emstor2$	6	Grönroos (2014)
Manure ash content	ash	0.08	IPCC (2006)
Max. CH_4 producing capacity, m^3/kg vs	$chmax$	0.24	Statistics Finland (2016)
Manure spreading			
Broadcast spreading			
Manure N evaporated as NH_3, %	$emspread1$	40	Grönroos (2014)
Injection			
Manure N evaporated as NH_3, %	$emspread2$	9	Grönroos (2014)
Autonomous soil emissions, kg CO_2-eq./ha			
Barley	$autoc$	1535	
Silage	$autos$	426	
Pasture	$autop$	1535	
Cultivation practices, kg CO_2-eq./ha			
Barley	$cultc$	362	
Silage	$cults$	136.5	
Pasture	$cultp$	362	
N applied to pasture land, kg N/ha	lp	220	
Other parameters			
Yield transport to processing, kg CO_2-eq./ha	$emtrans$	0.00696	
Crop drying, kg CO_2-eq./kg yield	$emdry$	0.028	
Mineral fertilizer manufacture, kg CO_2-eq./kg N	$emprod$	4.32	
Soybean meal manufacture, kg CO_2-eq./kg	$emsoy$	5.35	Opio et al. (2013)

Most values in Statistics Finland (2016) are originally obtained from IPCC (2006).