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***Summary** – The application of economic instruments to GHG emissions from dairy farms needs to rely on GHG indicators as actual emissions are impossible or extremely costly to measure. The choice of indicator impacts chosen abatement options, related costs and GHG actually emitted. A tool to quantify these relations is proposed which at its core consists of a highly detailed, mixed-integer dynamic programming model template able to cover a wide range of dairy farm characteristics and promising indicators. It allows deriving and comparing marginal abatement costs of GHGs emission for different farm types and indicators, informing the policy process about promising indicators, abatement strategies and related abatement and measurement costs.*

***Keywords:** marginal abatement costs, emission indicators, dynamic mixed integer programming, greenhouse gas emissions*

Le rôle clé du choix de l'indicateur d'émissions dans la définition d'une politique environnementale : l'exemple de la réduction des émissions de gaz à effet de serre dans des fermes laitières analysé à l'aide d'un modèle bioéconomique

Résumé – Pour évaluer les impacts de l'application d'instruments économiques destinés à réduire les émissions des gaz à effet de serre (GHG) des exploitations laitières, il s'avère nécessaire d'utiliser des indicateurs, étant donné que la mesure directe des émissions est impossible ou très coûteuse. Le choix des indicateurs peut orienter les options de réduction choisies par les fermiers, leurs coûts et les niveaux d'émission de GHG. Pour quantifier ces relations, l'article propose un modèle de programmation mathématique mixte linéaire dynamique capable de représenter différents types d'exploitation laitière et de simuler les impacts de mesures destinées à diminuer les émissions de GHG. Il permet de comparer les coûts marginaux de réduction des émissions entre les différents types d'exploitation et d'indicateurs et de donner des informations permettant de choisir les meilleurs indicateurs ainsi que les stratégies les plus adaptées.

Mots-clés : coûts marginaux de réduction, indicateurs d'émission, programmation mixte linéaire dynamique, émissions de gaz à effet de serre

JEL classification: D01, Q12, Q52

Acknowledgements
The research is funded by a grant of the German Science Foundation (DFG) with the reference number HO 3780/2-1. The authors would thank two anonymous reviewers for their comments.

1. Introduction

Agricultural production directly accounted for 13.5% of total global greenhouse gas (GHG) emissions (CH_4, N_2O, CO_2) in 2004 (IPCC, 2007) stemming from ruminant fermentation, fertilizer use and further farm processes. With 4% on global totals, more than a quarter of agricultural emission stems from dairy production alone (FAO, 2010), which is thus an important emitter of GHGs (Steinfield *et al.*, 2006; FAO, 2009). It is obvious that higher emission reduction targets, also for industrialized countries such as Germany, will require an inclusion of agriculture into GHG emission abatement efforts (*e.g.* BMELV, 2010), and, especially in Germany, dairy farming will be one of the key sectors.

From an economic viewpoint, promising policy instruments to steer abatement efforts are price-based such as emission taxes or tradable emission rights. Facing such instruments, firms will abate emissions as long as marginal abatement costs are lower than the emission price – which is either equal to the per unit tax or to the price of a tradable permit. Once the marginal abatement costs exceed the price, firms will either pay taxes or buy additional permits.

Accordingly, two main questions arise for an adequate policy design when targeting GHG emissions from dairy farms. Firstly, judging how costly certain reduction targets are requires knowledge about marginal abatement cost (MAC) curves for GHG emissions of CH_4, N_2O and CO_2 for single dairy farms and for the dairy sector. And secondly, an appropriate emission indicator is needed which can be implemented at farm level to account for GHG emissions. These two aspects are strongly interrelated, as the MACs will to a large degree depend on the chosen indicator.

But why is that the case? Such as we only pay income taxes on declared income, dairy farmers will only pay emission taxes on declared emissions. The abatement strategy of a farmer and the related costs will hence depend on how emissions are defined by the specific indicator chosen – a kind of GHG tax code –, and not on the physically emitted GHGs. Options which change emissions but are not accounted for will not be integrated in abatement efforts, even if they are less costly. If measurement of GHGs would be costless, we would not need an indicator, and there would be no difference between accounted and emitted GHGs. But GHGs from dairy farms are impossible or rather costly to measure due to the "non-point source" character of agricultural production which takes place in open, human managed biological systems (Osterburg, 2004). Accordingly, any policy instrument targeting GHG emissions from agriculture will have to rely on GHG indicators and to face the problem to find a balance between measurement and abatement costs in relation to real reductions of GHGs.

Indications on how to construct indicators can be drawn from promising GHG abatement options discussed in literature – a good indicator should take those options into account. Changes in animal diet, manure management and control of production intensity are possible examples of such options. However, studies analyzing abatement costs so far often use rather simple indicators which are based on activity levels where GHGs of the farm are calculated by multiplying herd sizes and acreages by a fix per head or ha emission factor (Breen, 2008; Pérez and Holm-Müller, 2007). These indicators are rather rough and do not account for promising abatement options, whereas fodder intake (De Cara and Jayet, 2000, 2001 and 2006) or milk yield per cow are more precise and closer to the scientifically discussed abatement options. But especially fodder intake is also difficult to control.

Consequently, the questions resulting from the above stated problems are: *(i)* What are promising abatement options of GHGs in dairy farming? *(ii)* What are the abatement and measurement costs for different types of dairy farms and the dairy sector as a whole under different indicators and emission targets? *(iii)* What is an appropriate methodology to derive these costs? And *(iv)*, what drives the abatement costs under different indicators?

The objective of this paper is to present a core element of the methodology to answer these questions: a farm-specific economic simulation model which is able to cover a great variety of GHG abatement options and to derive farm specific marginal abatement cost curves for different emission indicators. Illustrative differences in MAC shapes depending on farm characteristics and indicators will be shown, using four different farms (differentiated by starting herd size and milk yield) under four GHG emission indicators. Furthermore, the paper will give first indications for the cost effectiveness of different indicators related to abatement efforts in dairy production.

The main contribution of this paper is the presentation of a highly detailed farm-specific bio-economic model, which incorporates major technological and financial interactions in dairy production and allows simulating economically optimal abatement strategies under different emission indicators and emission targets. The modelling approach must capture core characteristics of dairy farming. One key characteristic are long lasting investments in stables and milking parlours, which account for a larger part of production costs. The model template must hence cover a longer planning horizon. Secondly, the (bio-) dynamic character of dairy production must be taken into account. Variables like *e.g.* biomass, herd size and distribution of milk yield in the herd as well as existing firm endowments such as stables, machinery, equity or property rights to land or subsidies are to a larger extent state variables which are not or only to a certain extent controllable in period t, but depend on control variables of former periods (Kennedy, 1987). In addition competitiveness, asset fixity and rapid technological change are characteristics of agricultural production (Rausser and Hochman, 1979). Thirdly, decision variables are partly continuous (*e.g.* amounts of fertilizer, cropping land) and partly not (*e.g.* investment or labour use decisions). Therefore a dynamic mixed integer programming model approach (MIP) as proposed by Nemhauser and Wolsey (1999) and Pochet and Wolsey (2006) is to be used to respect also integer or binary decision variables.

The following section will provide a short literature review, discussing the state of the art in the research field of deriving marginal abatement costs for GHG emissions in agriculture. From there, features of the proposed model template will be motivated. Subsequent sections focus on specific modules of the model template and their relations. After a detailed description of how abatement and marginal abatement costs are derived, farm characteristics of our illustrative simulation runs will be delineated. After discussing the resulting outputs, we will summarize and conclude, specifically regarding further research activity.

2. Literature review

A detailed comparison of different model approaches for the derivation of MACs for GHG emissions is found in Vermont and De Cara (2010). They point out that so-called supply side models are best equipped to model what is normally understood as MAC curves because of their relatively detailed technological description. Many studies estimate MAC curves based on supply side models for European agriculture only considering changes in activity levels (*e.g.* Breen, 2008; De Cara *et al.*, 2005). Besides herd size changes or changes in cropping area, Durandeau *et al.* (2010) also took adjustments in fertilizer use into account when evaluating abatement costs for reducing N_2O-emissions from soil in an application to a French region. In a EU-wide application, Pérez and Britz (2010) considered changes in herd size, yields, cropping areas and fertilizer practice. A model approach that already implements more detailed emission calculations, based also on ruminant fermentation, feed intake and fodder composition is presented by De Cara and Jayet (2000). The authors developed a linear programming (LP-) approach for French agriculture to evaluate GHG abatement costs, which has been subsequently improved (De Cara and Jayet, 2001 and 2006). The mentioned studies model either a regional aggregate of all farms or aggregate of farm types for rather large regions, carrying the risk of aggregation bias (Pérez *et al.*, 2003) and do not allow analyzing in detail differences evolving from farm characteristics.

Equally, the approaches are comparative static so that dynamic aspects e.g. relating to herd management and investments are not taken into account, carrying the risk to overestimate MACs. In Europe, Hediger (2006) incorporates abatement options in a recursive dynamic modelling exercise to consider investments and further time dependent aspects in an application to whole Swiss agriculture. The results underline that investment-based abatement options should be considered, requiring a dynamic perspective as offered by dynamic programming. An example for a dynamic approach relating to herd management is presented by Huirne *et al.* (1993) for replacement decisions of sows, but the basic structure can easily be transferred to dairy cows.

Existing studies calculate emission abatement costs given a specific GHG indicator, not investigating differences between GHG emissions, abatement strategies and costs under different indicators. Only Durandeau *et al.* (2010) highlight that the choice of the emission indicator is a key question in the design of emission policy schemes, as it will have a strong influence on abatement, implementation and monitoring costs. As underlined in the introduction, a cost-effective abatement is strongly dependent on the design of an emission indicator, but studies, which discuss and compare varying indicator systems for GHG abatement in agriculture do not exist.

Weiske and Michel (2007) show modelling results of different abatement strategies in dairy production based on an economic engineering model. They evaluate the abatement potential and related costs of different feed mixes and conclude that promising GHG- reducing feeding strategies depend on farm characteristics. Accordingly, an appropriate modelling approach should allow for endogenous and variable adjustments of the feed mix while properly reflecting the impact of feed mix changes on emitted GHGs.

In order to improve on existing studies, promising abatement options for GHG for dairy farms need to be collected and integrated in the model template. Abatement strategies that are mentioned in literature (*e.g.* by Bates, 2001; Flachowsky and Brade, 2007; Guan *et al.*, 2006; Jentsch *et al.*, 2007; Johnson *et al.*, 2007; Kamra *et al.*, 2006; KTBL, 2002; McGinn *et al.*, 2004; Osterburg *et al.*, 2009; UNFCCC, 2008; Weiske, 2006) range from variable feed adjustments to investment decisions for manure coverage. To evaluate the different options, studies like Boadi *et al.* (2004) give a qualitative benchmark of the practical availability and feasibility of the different strategies, here for the abatement of methane. Emission parameters and emission functions linked to production activities will be based on literature, *e.g.* IPCC (2006) and Dämmgen (2009). Several studies do not only list abatement options, but also quantify reduction potentials and related costs, *e.g.* Weiske (2006). In the following the methodology and construction of the model is described. After the explanation of interactions between the different dairy farm production modules, the derivation process of MACs is described. An analysis of illustrative model results will complete this part and highlight areas of further research and model expansion.

3. Methodology

Our single farm model template, named "DAIRYDYN", is based on mixed-integer, fully dynamic linear programming. A programming approach allows describing in great detail the technological relations between different decision variables as discussed below. Integer decision variables are necessary to account for the non-continuous character of labour use and investment decisions. Furthermore a fully dynamic approach is deemed important to account for both the forward looking character in developing farm business plans incorporating long-lasting investments and the strong inter-annual dependencies in dairy herd management. It allows depicting factors impacting the development of dairy farms independently from GHG related policy instruments (*e.g.* breeding to higher milk yields per cow), which might also change GHG emissions. A fully dynamic approach allows comparing baseline developments (without emission ceilings) against those under emission reductions to identify GHG abatement activities that are implemented additionally. Otherwise, GHG abatement activities additional to ongoing processes may be obstructed (Smith *et al.*, 2007).

4. The Model

4.1. Overview

We assume a fully informed, rational, risk neutral decision maker maximizing net present value of expected profits under different states-of-nature with given probabilities. The states of nature currently relate to different key prices (milk, beef, concentrates) faced by the farmers. The famers draw revenues from subsidies (single farm payment), selling farm products (cash crops, milk, calves, slaughtered cows) and selling or renting out assets (land, interest on equity, off-farm labour), while facing expenditures from buying inputs (fertilizer, concentrates, labour...) or investment goods (land, machinery, stables), from paying back credits and interest on them, as well as from given household expenditures. A positive cash balance has to be maintained, if necessary by external financing. The accumulated cash balance minus open loans at the end of the planning horizon is the objective value.

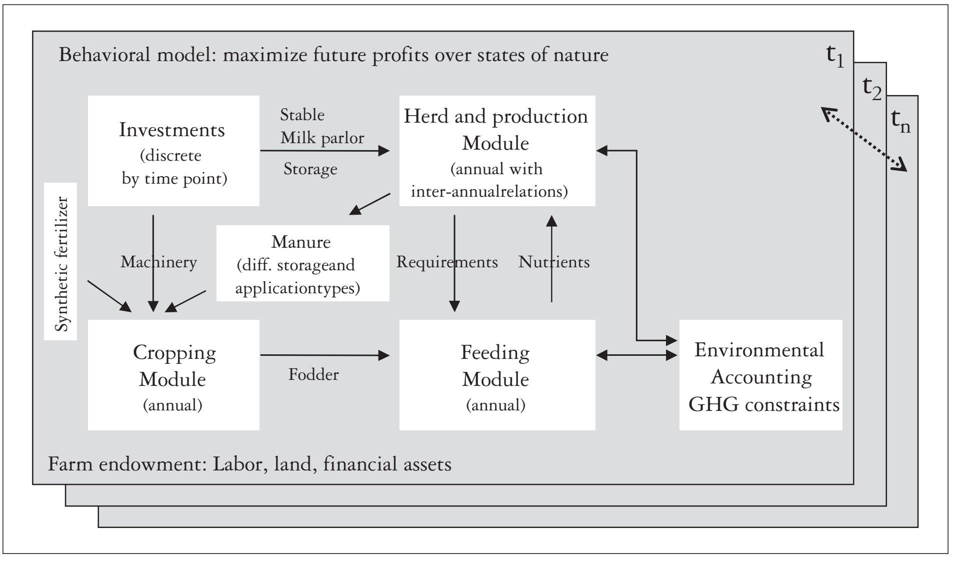
The model template consists of different modules describing sub-systems of a dairy farm level. Figure 1 visualizes these modules and specific interactions between them over several time periods ($t_1 - t_n$) depending on the relevant planning horizon.

The *herd and milk production module* covers decisions concerning replacement of cows, growth or reduction of herd size as well as changes in milk yield of the herd. Female herds (dairy cows, heifers, female calves) are differentiated in strata by their maximum milk yield. A dairy cow with a given milk yield potential gives birth to calves with a different milk yield potential from which the farm can select, depending on transition probabilities between generations. The model thus describes endogenously the development of the milk yield potential in the herd. A sharper selection reduces possible herd expansions (at least in the current version where females cannot be bought). At the same time, cows with a higher milk yield are characterized by a lower number of lactations and higher labour needs, and as discussed in the next paragraph, by different feeding requirements. Decisions in herd module are closely interlinked with the feeding module.

The *feeding module* consists firstly of requirement functions (energy, protein, max and min dry matter and fibre etc.) for each herd. For dairy cows, these requirements are defined for different lactation periods and depend on the average daily milk yield in these periods. Secondly, it comprises endogenous variables which distribute feeding stuff to livestock categories which need to cover livestock nutrient requirements. These variables are differentiated by herd, year, lactation period and intra-yearly planning period.

The *cropping module* describes land use, distinguishing between arable and grassland activities. The latter are differentiated by intensity (number of cuts and grass yield) and management type (grazing or cutting). Grassland activities deliver certain amounts of grass in different intra-yearly planning periods. Cropping activities demand machinery – link to the investment module – and labour, and are characterized by costs and, if applicable, market revenues. Furthermore crop nutrient requirements and balances are introduced to model endogenously the application of mineral fertilizer and manure.

Figure 1. **Overview on model template**



Source: Own illustration

The *investment module* covers endogenous decisions about investments in new stable places or milking parlour, liquid manure reservoirs and machinery. Additionally, the template captures labour by intra-annual planning periods, which allows farm family members to work off- or on- farm and to hire external labour.

The *fertilizing and manure handling module* depicts synthetic fertilizer use and manure handling, in the latter case capturing different storage types (subfloor or in surface reservoirs), the possibility to cover surface reservoirs with straw or foil and different application techniques. These details are introduced to account for NO_x and further N-losses dependent on stable, storage and application type.

Wherever necessary and applicable, decision variables are linked to emission parameters for CH_4, N_2O and CO_2. That means that selected variables of the model carry emission factors according to the applied emission crediting system (GHG indicator) to calculate endogenously an overall GHG amount from the production program of the farm.

Attention is paid that the different modules cover relevant abatement options for GHGs discussed in literature (*e.g.* increasing milk yield per cow, investments in certain stable types, manure storage coverage, use of feed additives, changes in feed mix and variation of herd size) with their specific mitigation parameters, their interactions, the associated costs and further attributes for *e.g.* labour need or content of feed stuff. Simulations with the template then also take indirect impacts of these options on the farm program (*e.g.* changes in the feed mix impacting crop shares, crop management and manure management) and thus profits into account.

To build up farm models with a highly disaggregated production process of dairy farming, information are taken from detailed farm management handbooks such as

KTBL (2008, 2010) which also cover investment costs for machinery, building and other farm equipment. Abatement simulations are based on GHG emission restrictions, which determine an upper limit for GHG emissions of the whole farm. These are defined based on decision variables and attached GHG emission factors, the latter depending on the specific emission indicator chosen. New or stronger restrictions might require adjustments in farm program. The resulting changes in farm profits are then used to derive abatement and marginal abatement costs, specific for the farm, the indicator and the GHG reduction level. This process will be described more detailed in section 5.

4.2. Detailed presentation of specific modules

4.2.1. Herd and production

The herd module captures different decision possibilities to control herd size and milk yield during the planning horizon. It has an annual resolution and differentiates between dairy cows, heifers and female calves for replacement and female and male calves sold. Dairy cows, female calves and heifers for replacement are further differentiated by their potential milk yield. Consequently, in any one year, the herds simulated for a farm will typically consist of different groups of dairy cows, female calves and heifers for replacement differentiated by their potential milk yield. Starting with the initial herd with a specific genetic production potential, cows give birth with a certain probability to calves with different milk yield potentials, which partly exceeds the genetic potential of the mother. The model can endogenously choose how many females of a specific potential are raised for replacement or sold. This allows hence depicting the trade-off between sharper selection and herd size increase. The calves born in a given year replace cows three years later, introducing inter-annual relations between the groups of different milk potential over time. Cows reaching their maximum number of lactations, which decrease with increasing milk yield potential, need to be slaughtered; additional slaughter is possible to reduce the herd size. In order to retain a flexible intensity management the genetic milk yield potential needs not to be fully exhausted (*e.g.* to manage years where fodder availability is low or feed prices are high). Furthermore, labour and feed requirements (see below) and other costs for dairy cows are differentiated by potential milk yield.

4.2.2. Feeding

Requirement functions are specified for the different herds according to IPCC (2006). For cows, to give an example, requirements depend on animal weight, actual fat corrected milk yield, the latter differentiated in 200 kg steps, and are specified for 5 lactation periods (30-70-100-105-60 days, where the last 60 days are the dry period) with different average daily milk yield. The functions depict energy, protein, fibre min/max and dry matter min/max, respecting the rumen capacity. In addition, max/min of certain feed are defined. These requirements enter constraints in the model template, differentiated by year, state of nature (SON) and herd – for dairy cows differentiated by milk yield –, lactation period and intra-yearly planning period, the latter to take into account available fodder from grazing. These constraints need to be covered by feeding activities, which are either linked to fodder production and thus cropping activities or purchases of concentrates. The feeding blocks consequently comprise a very large number of endogenous variables. Whereas the farmer takes yearly decisions about herd size and composition only in averages over the SONs, feeding can be flexible adjusted to the SON.

4.2.3. Cropping

The cropping module covers different cropping activities for arable and grassland. Cash crops on arable land such as cereals or oilseeds compete with fodder production like maize silage. On grassland, silage or pasture in different management intensities are considered. The farmer can sell, buy or rent out land. The crop mix is restricted by maximum rotation share for each crop, where deemed appropriate. Cropping decisions are differentiated by crop, year, SON and, where applicable, management intensity. Yields in pasture are differentiated by planning period and, together with other types of fodder production, directly interact with the feeding module. Crops are further characterized by exogenously given labour and fertilization needs for nitrogen, other operation costs, yields and related prices, the latter can be differentiated by SON. Furthermore, the activities in the cropping module demand certain amounts of machinery available, which have to be acquired if not yet in the inventory. The above described herd and production module produces different amounts of slurry, depending on herd composition and sizes and the stable system.

4.2.4. Manure handling and fertilization module

The module deals with different manure storage as well as mineral and organic application techniques, which might differ in NO_x emissions, providing a further link between the herd and cropping modules. Manure excretions can be either stored sub-floor or in differently sized surface manure reservoirs and the farm has to maintain certain storage capacity in relation to yearly manure output. The silos can be additionally covered by straw or foil to reduce emissions during storage. Manure can either be distributed based on spreader, a drag hose or injected. Maximum application rates and periods where manure application is forbidden are taken into account according to the German implementation of the Nitrates directive. Further on, depending on the crop, further periods might be blocked for manure application (e.g. applications after maize has reached a certain size). Besides manure, synthetic fertilizer can be used to cover plant nutrient demands.

4.2.5. Investments and finances

Investment decisions are implemented as binary variables with a yearly resolution [1]. Whereas feeding and cropping decisions are rather flexible and can be adjusted to changes in prices, we allow decisions upon herd size and composition as well as upon investments only in average of the SONs. Cropping activities require certain machine

[1] It is possible to restrict investment decision to specific years to keep the number of binary variables at a manageable size.

hours of *e.g.* tractors and ploughs, which have to be replaced when their maximum of operation hours is reached. Different stable types (for calves, heifers, cows) in differing sizes are offered by the model to allow for building up new herd capacities or to replace old stables, which have reached the end of their useful life (30 years lifetime). Stable types differ in investment costs and labour hours per stable place. As mentioned above, surface manure reservoirs are offered in different sizes and coverage techniques. The demanded machinery by the cropping activities as well as investments in buildings can be financed either from accumulated cash or credits. The latter are differentiated by pay-back time and interest rate. Accumulated cash draws interest. It is assumed that stables cannot be sold and that the demolition costs of the stables at the end of their usage equate the residual value of sellable technical equipment.

4.3. GHG indicators

In dairy production, manifold sources of GHG emissions exist. According to IPCC guidelines and the way the European emission trade scheme is implemented, only direct emissions of CH_4, N_2O and CO_2 from on-farm processes are accounted for in the model. The system border is hence the farm gate, so that results should not be confused with lifecycle-assessment.

Enteric fermentation as well as manure management are the main sources of CH_4 in dairy production systems with the majority stemming from digestive processes. Nitrous oxide emissions primarily stem from processes in agricultural soils after N application of fertilizers or during crop growth and chemical N conversion processes in soils. As N_2O production is an aerobic process and manure is mainly anaerobe, only minor amounts of nitrous oxide emissions are caused by manure storage or application. CO_2 is assimilated by crop lands and also emitted by soils if *e.g.* permanent grassland is ploughed. So far, CO_2 assimilation by crops is not implemented in the model, but following Boeckx and Van Cleemput (2001) CH_4 deposition by agricultural soils is accounted for. So depending on the cultivation of land, soils can become a net source as well as a sink over a full year.

All decision variables in the model template might carry an emission factor expressed as CO_2 equivalents (single gas emissions of CO_2, N_2O and CH_4 multiplied with global warming potential of 310 for N_2O and 21 for CH_4 (UBA, 2009)) and thus enter the GHG emission constraint. The emission factors are either directly taken from literature, calculated based on literature based emission functions or, in future, based on measurements at an experimental farm of Bonn University. A specific set of emission factors is termed a GHG emission indicator and thus represents a specific accounting system for GHGs from dairy farms. The minimal profit loss and related farm program under a GHG ceiling depend on the interaction between the decision variables and that ceiling via the emission factors. As depicted in the objective of this paper, different emission indicators are to be analyzed concerning their impact on the shape of MAC curves and related abatement strategies. These indicators are more or less complex and accurate. They also relate to different decision variables (number of cows, milk yield per cow, C and N in feedstock, arable activities, fertilizer intensity...)

and thus determine the possibilities of farmers to react to emission ceilings. Figure 2 on the next page depicts an overview on the indicators.

The different indicators are mainly based on the IPCC (2006) guidelines [2], which comprise so-called tiers of increasing complexity to calculate GHG emission. Tier 1 provides the simplest approach to account emissions using default parameters e.g. per animal. We use Tier 1 as far as possible to define our simplest indicator termed *actBased*, where emission factors are linked to herds and crop hectares, only. The exemptions from the IPCC methodology are manure management and fertilization where IPCC links emission factor to organic and synthetic fertilizer amounts. We thus assume average excretion and fertilizer application rates to derive per animal or per ha coefficients.

A somewhat more complex indicator called *prodBased* links emission factors to production quantities of milk and crop outputs, see details in table 1 below. Generally, at the assumed average yields, the two indicators yield the same overall emissions. Compared to the activity based indicator, famers have somewhat more flexibility as they might *e.g.* switch between different grass land management intensities to abate emissions.

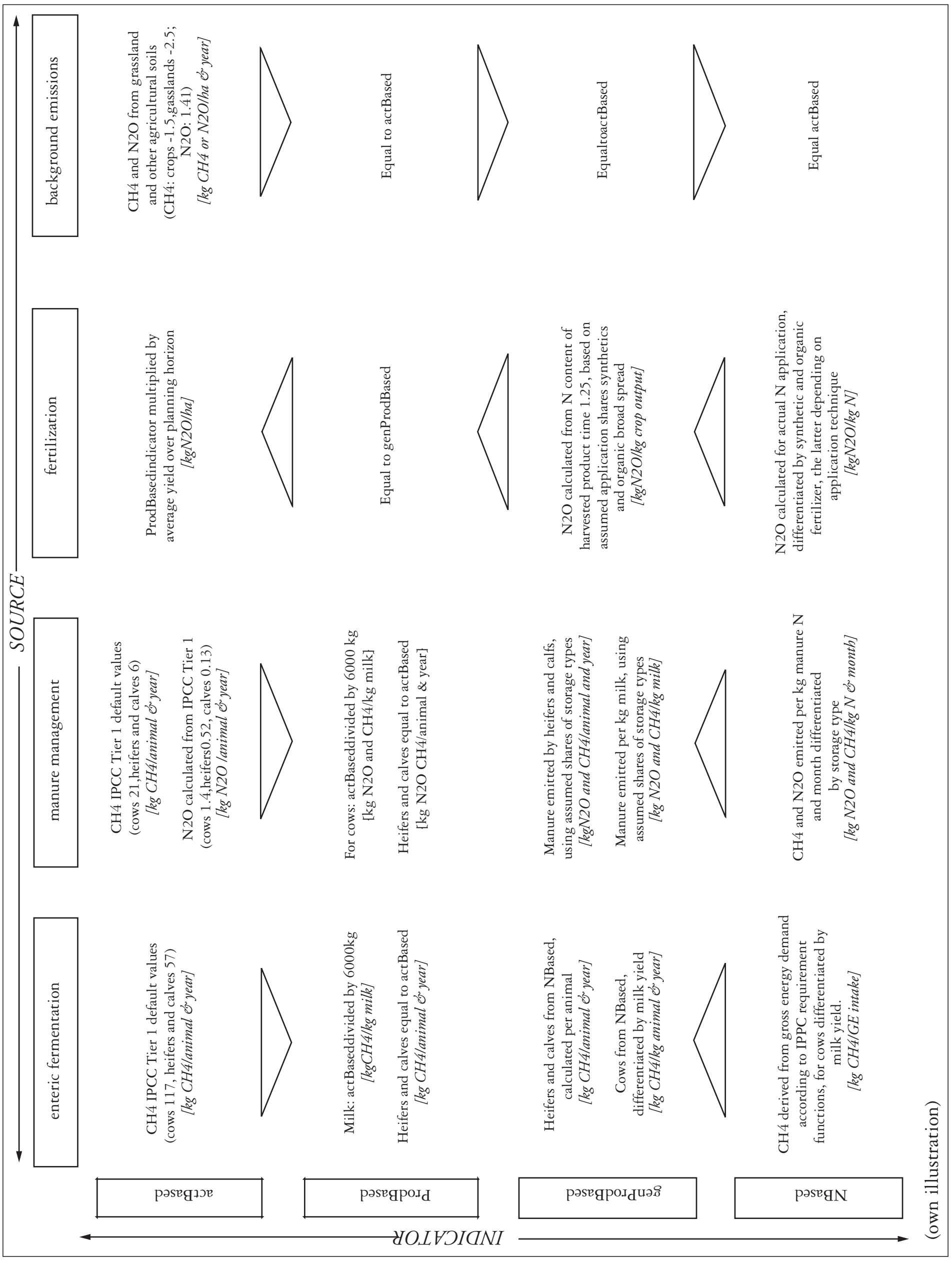
The most complex and also presumably most accurate indicator is called *NBased*. Values for enteric fermentation are calculated from the requirement functions, for energy based on IPCC guidelines, which also drive the feed mix. For manure management, emissions are linked to the amount of manure N in specific storage types in each month. For fertilization, the emission factors are linked to distributed nitrogen differentiated by application technique. The indicator thus gives the farmer the chance to abate nitrogen losses by changing storage types, storage periods or the fertilization application technique, beside changes in herd sizes, herd structure or the cropping pattern.

An intermediate indicator between the prodBased and NBased one is called *genProdBased*. Its emission factors are linked mainly to output quantities but as far as possible derived from the NBased one assuming fixed application shares of synthetic and organic N. The differences, as seen from figure 2, stem from the calculation of emissions from enteric fermentation and manure management. Specifically, the indicator introduces milk yield dependent emission factors, which reflect that higher milk yields reduce per litre emissions by distribution the maintenance need of the cow over a larger milk quantity, diminishing from 0.81 kg CO_2-equ. *per* kg milk for a 4000 liter cow to 0.40 kg CO_2-equ. *per* kg milk for a 10000 liter cow (see table 1). The yield level dependent output coefficients per kg of milk are hence the major advantage of the genProdBased indicator compared to the prodBased one.

No difference in emission calculation between the indicators is made for the background emissions coming from soils as seen from the figure 2. The chosen default values per ha are taken from Dämmgen (2009) and Velthof and Oenema (1997). Obviously, moving from the bottom of figure 2 to the top, the aggregation level of emission relevant model variables increases which means a loss in detail concerning the decision variables addressed by the indicators.

[2] Equations and parameters of sections 10 and 11.

Figure 2. **Indicator schemes**



(own illustration)

The parameters for the three simpler indicators are shown in the following table. Computations for the NBased indicator are also taken from the IPCC (2006) guidelines, focusing on equations from subsections 10 and 11. For the direct emissions from managed soils equation 11.1 is taken with the corresponding auxiliary calculations and default emission parameters. Equations 11.9 and 11.10 are used to

Table 1. **Emission parameters in kg CO_2-equ, by indicator**

	Calculation unit	actBased	proBased	genProdBased	assumed av. Yield per ha or head
Cere	ha	2020.83			
Cere	prodQuant		241.48	241.48	8.3 t
Oils	ha	1585.08			
Oils	prodQuant		505.09	505.09	3.1 t
Rest	ha	588.47			
Rest	prodQuant		140.64	140.64	4.1 t
MaizSil	ha	1864.70			
MaizSil	prodQuant		41.44	41.44	44.9 t
idle	ha	406.93	406.93	406.93	
grasSil	prodQuant		46.62	46.62	25.4 t
gras20	ha	1188.70			
gras29	ha	1188.70			
gras34	ha	1188.70			
past33	ha	2660.32			
grasPasture	prodQuant		80.62	80.62	32.9 t
milk	prodQuant		0.56		6000 kg
cows4000	prodQuant			0.81	
cows5000	prodQuant			0.67	
cows6000	prodQuant			0.58	
cows7000	prodQuant			0.52	
cows8000	prodQuant			0.47	
cows9000	prodQuant			0.43	
cows10000	prodQuant			0.40	
mCalvs	head	52.29	52.29	27.12	
fCalvsSold	head	52.29	52.29	27.12	
fCalvsRais	head	1363.30	1363.30	707.00	
heifers	head	1484.20	1484.20	1358.50	
cows	head	3332.00			

Sources: Own calculation and illustration following IPCC (2006) and Dämmgen (2009) derive indirect emissions from soils, only the default values for background soil emissions (N_2O) are taken from Velthof and Oenema (1997) due to a correction in emission level [3]. Emission calculations from enteric fermentation and manure management are also based on IPCC stemming equations (subsection 10), using where possible also Tier 2 equations.

5. Derivation of marginal abatement costs for single firm

Under a given indicator, a stepwise reduction of the emission constraint will potentially lead to a stepwise reduction in farm profits. Relating the change in emissions to the changes in profits allows calculating the total and marginal abatement cost.

In the following, em_{0j} are the emissions measured with indicator j under the profit maximal farm program without any emission target, where the zero characterizes the reduction level. The reader should note that different indicators are attaching different GHG emissions to the very same farm program.

To derive marginal abatement cost curves, an emission ceiling will be introduced and stepwise lowered. n reduction steps, each with the same reduction relative to the base em_{0j}, will be taken, leading to objective values from π_{0j} to π_{nj} (where π_{ij} is the value of the objective function in simulation step i, using indicator j; with i from 0 to n). Let rec_i denote the emission ceiling in step i relative to baseline emissions. The maximal profit under the derived absolute ceiling $rec_i em_{0j}$ is restricted according to:

$$\sum_k ef_{jk}\, x_k \le rec_i\, em_{0j} \tag{1}$$

where x_k are the decision variables and ef_{jk} the emission factors attached to them under indicator j, *i.e.* the CO_2 equivalent emission accounted per unit of variable k.

The difference in profits between π_{0j} – the profit without a GHG restriction – and π_{ij} measures the profit foregone due to ceiling $rec_i em_{0j}$ and defines hence the total *abatement costs (AC)* for the reduction level of step i and indicator j:

$$AC_{ij} = \pi_{0j} - \pi_{ij} \tag{2}$$

A stepwise reduction of the emission constraint leads to a sequence of changes in farm program and related profit losses. Relating these differences in profits to the difference in emissions defines the simulated *marginal abatement costs* (MAC):

$$MAC_{ij} = \frac{\pi_{i-1,j} - \pi_{i,j}}{em_{i-1,j} - em_{i,j}} \tag{2.1}$$

When comparing different emission indicators we face the problem that the MACs of each indicator relate to its specific GHG accounting rules. Accordingly, the MACs of different indicators cannot be compared directly.

[3] IPCC default value is 10 times higher because the underlying study bases on peat soils.

From a policy perspective, we would like to assess costs and benefits of choosing a certain indicator and ceiling based on the GHGs physically released from the farm, and not the GHG accounted by a specific indicator. Indicators might over- or underestimate physical GHG emissions and thus under- or overestimate the "true" MACs.

In an ideal world, we would be able to derive the "real" GHG emissions from the farm program. As this is impossible, a so-called *reference indicator* will be constructed. It will use the best available scientific knowledge to derive from the farm program, *i.e.* based on all available decision variables, a total GHG emission estimate from the farm. The underlying calculation could be highly non-linear and complex and need not necessarily be integrated in the model template itself. Equally, it does not matter if it could be implemented in reality on a dairy farm given its measurement costs. It simply serves as a yard stick to normalize GHG emissions from different, simpler, but more realistic and applicable indicators. Relating profit losses under different indicators and indicator-specific GHG emission targets to the GHGs abatement under the reference indicator r at the simulated farm program allows deriving normalized marginal abatement cost curves which can be compared between indicators:

$$MAC_{ij}^{norm} = \frac{\pi_{i-1,j} - \pi_{i,j}}{em_{i-1,r} - em_{i,r}} \tag{2.2}$$

This will show under which indicator the highest efficiency will be obtained, meaning that "real" abated emissions of the optimized production portfolios of the farms are calculated and related to the abatement costs caused by different emission indicators. Currently, we use the NBased indicator defined above as the reference indicator.

According to the stated objective of this paper, we formulate a few hypotheses and test them with illustrative model applications:

1. MACs depend on farm characteristics.
2. The model creates AC which are theoretically consistent – *i.e.* increasing in emission ceilings – and plausible from an engineering and economic viewpoint.
3. Abatement strategies depend on farm characteristics and chosen indicator.
4. Indicators show different economic efficiency based on their normalized MACs.

6. Technical implementation

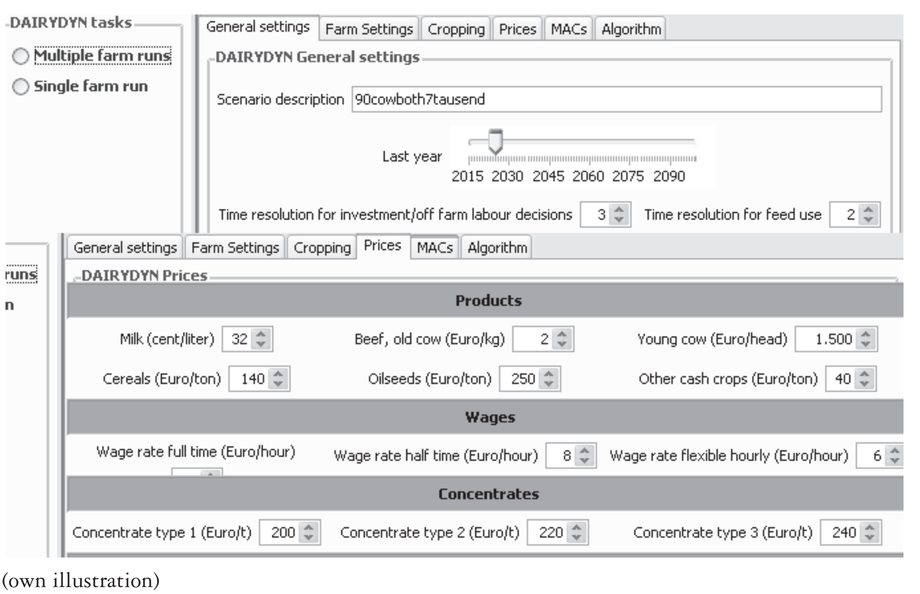
The model template is realized in the *General Algebraic Modelling System* GAMS (Rosenthal, 2010). It is complemented by the so-called coefficient generator, *i.e.* GAMS code, which parameterizes an instance of the model template based on bio-physical relations (such as requirement functions for animals) and engineering data (such as look-up tables with investment and other costs and labour requirements per stable place and year for different stable types). The coefficient generator is designed to be generic enough to cover relevant dairy farm types in Germany and to define all necessary model parameters from a few, decisive initial farm characteristics such as given herd size and milk yield, land, labour and stable endowments.

Based on the current, not yet fully developed template, a typical application for one farm over a planning horizon of 15 years leads to a MIP problem with about 20 thousand variables of which about 400 are integer. An efficient MIP solver combined with an efficient solution strategy to handle the step-wise GHG reduction is hence needed to keep overall solution time manageable. We opted to apply CPLEX 13.2 (IBM, 2011) in parallel solving mode combined with automatic tuning, using integer re-starts from previous solves and MIP solution tolerances derived from the objective value in the reference and solving on a performing 8 core computing server. Equally, in order to reduce model size, some decision variables in the model relate to several years and re-investment are only possible at specific time point and not in each year. These settings can be changed in sensitivity experiments to verify that they have on serious impact on results.

Solving a single model instance for one indicator and emission ceilings with a 15 years planning horizon takes between 10 and 60 seconds. Accordingly, a run to simulate MACs for four indicators and twenty reduction steps easily can take as long as 60 minutes.

A Java based Graphical User Interface [4] (GUI, see figure 3) allows defining the farm types, generating an instance of the template model, its application on a set of indicators and GHG reduction steps and result analysis based on tables and graphs.

Figure 3. **Sections of the graphical user interface**



(own illustration)

[4] The exploitation part draws on the CAPRI Graphical User Interface (Britz, 2011).

7. Illustrative application

For the first step, different dairy farm types (differentiated *e.g.* in starting size and milk yield potential) are simulated under the four different emission indicators discussed above to show the impact of indicators on the differences in costs to abate emissions and to underline the indicator-dependent choice of abatement options as well as the differences concerning the accuracy of different indicators.

7.1. Main characteristics of the modelled farms

For our illustrative experiments, we simulate four farms differentiated by initial herd size (60 or 90 cows) and cow milk yield in the first simulation year (5000 or 7000 kg per cow and year).

Because of the bigger initial herd size, the 90 cow farms are endowed with a family work force of 2 instead of 1.5 annual labour units, further on, it possesses more land and benefits from lower labour need per animal compared to 60 cows farm. The planning and thus optimization horizon is assumed to end in the year 2025 with a construction year of the stables in 1995 (adapted to the assumed useful live of 30 years for buildings). The average price for milk is fixed at 0.32 €/kg. The runs encompass three states of nature: one with average prices, one with 20% higher prices for animal products and one with an increase in crop and concentrate prices by 20%. Abatement options depend on the chosen indicators as discussed above. The analysis is complemented by a sensitivity analysis for how manure application is handled. In the standard model, the farm spreads manure with own equipment so that switching the application technique requires investments. In our sensitivity experiment, we let the farm use contract work instead: that leads to somewhat higher per unit costs if the equipment would be fully depreciated over the planning horizon (which does not happen in our experiments), but gives the farm more flexibility.

8. Results

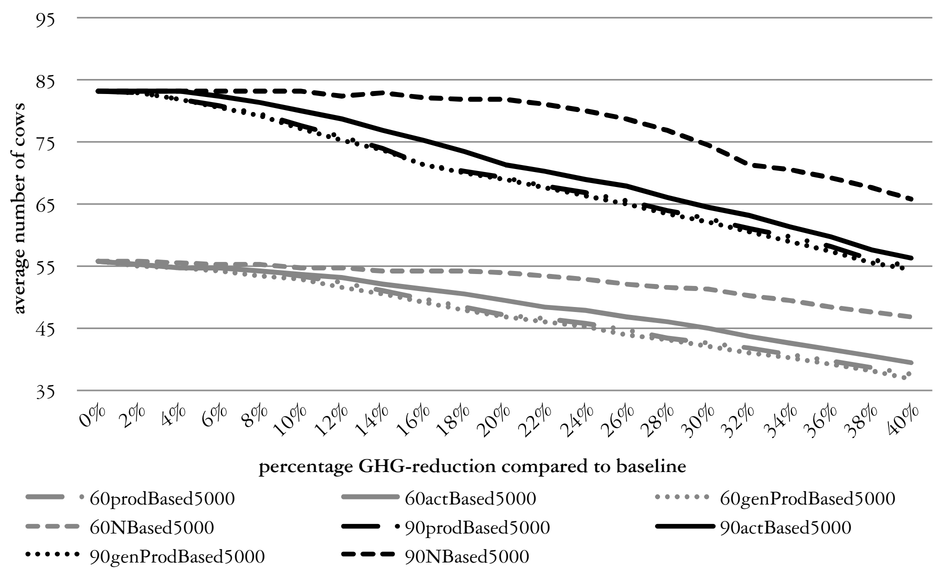
8.1. Herd sizes

The following figure 4 visualises the average herd sizes over the whole planning horizon, under different GHG reduction levels for the case of 60 and the 90 cows initial herd size and an identical initial milk yield of 5000 kg head^{-1} year^{-1}.

Note that in base run, the farm will typically towards the end of the simulation horizon reduce its herd to avoid raising calves and heifers to replace cows. The herd is sold in the last year at an assumed relatively low price, which is below the endogenous replacement cost if cows are not used the full number of lactations. That explains why average herd sizes are somewhat below the initial ones.

The graphic highlights that herd size reductions differ strongly between indicators, but that relative reductions between the 60 and 90 cow farms are quite similar. The largest reductions are found under the prodbased and genProdBased indicators, followed by the actBased indicators whereas the NBased indicator requires the smallest herd size adjustments.

Figure 4. **Average herd size over planning horizon for different GHG reduction levels**



(own calculation and illustration)

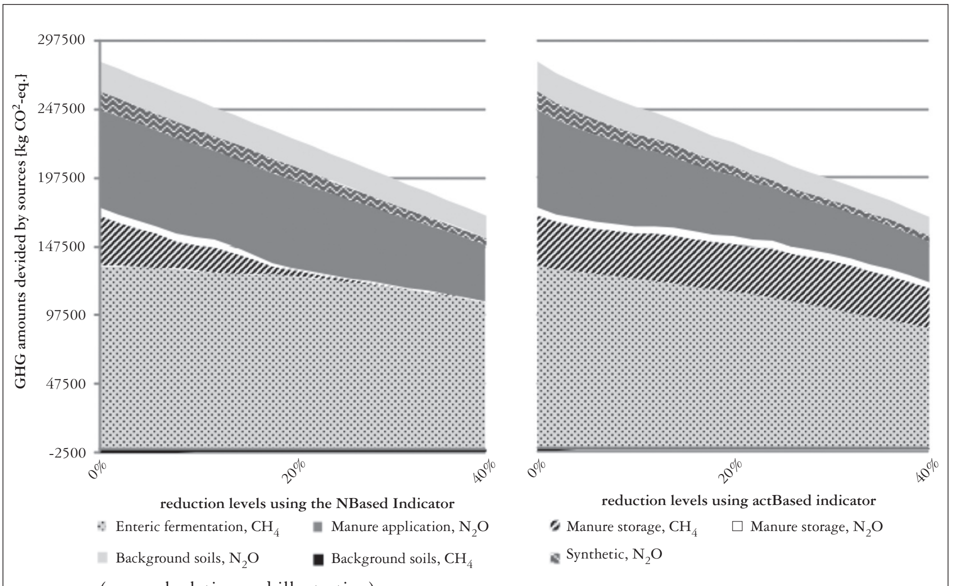
The sharper reduction under the production based indicators look at first glance astonishing, as the emissions per cow are higher under the activity based indicator for a 5000 liter cow. For the production based indicator, the default emissions per cow of ca. 3300 kg CO_2 equivalents under the activity based indicator are converted assuming a milk yield of 6000 l. Accordingly, a 5000 liter cow will emit only around 2750 kg CO_2 equivalents under the production based indicator (compare table 1 above). So why does the farm need to reduce its herd size more under the indicator prodBased with the lower emissions per cow? The reasons are twofold. Firstly, abatement efforts of the farms are defined relative to the indicator. So while indeed total accounted emissions under the prodBased indicator are lower, the relative reduction required is the same. And secondly, linked to that reason, due to lower emissions per cow under the production based indicator, the share of emissions from crops in the baseline is higher compared to the actBased indicator. Emissions from crops are more expensive to abate under that simple indicator, as their reduction requires giving up own fodder production and replace it by concentrates. The GHG emissions linked to concentrate production (*e.g.* fertilizing of cereals or oilseeds used for cake production and related background emissions from soils) would be accounted in other farms or even other countries, underlining again the importance of the system boundary definition.

The NBased indicator affects herd sizes only at higher reduction levels as cheaper abatement possibilities such as changing the manure storage type are used which are not accounted for by the other indicators. That allows abating 40% of the initial GHGs with herd size adjustments of –16% (60 cows) resp. –20.9% (90 cows), whereas the other indicators require reductions between –29.4% and –34.6%, depending on the indicator and herd size.

8.2. Abatement strategies under different indicators

Figure 5 below highlights differences in abatement strategies between the NBased and a simpler one, the actBased indicator, using results for the farm with an initial herd size of 60 cows and 5000 liter as an example. The graphic shows cumulated source specific emissions (expressed in CO_2-equivalents) based on the accounting rules of the NBased indicator. The reader is reminded that emissions under the activity based indicator are however reduced according to default emission factors attached to herds and crop hectares found in table 1.

Figure 5. **GHG by sources for 60 initial cows with 5,000 kg yield level, emission restrictions based on actBased indicator**



(own culculation and illustration)

The chart on the right hand side illustrates GHGs emitted from different sources when the farm has to abate according to the activity based indicator. It first underlines that enteric fermentation and manure application are the two dominating sources of emissions in our example farm. One can clearly see that there is an almost linear reduction of almost all sources under the activity based indicator. The decrease in CH_4 from enteric fermentation (34% reduction compared to baseline) is linked to the reduction of the herd size, whereas emissions from application of manure and synthetic fertilizers as well as background emission from soils are driven by a proportional reduction in land use: the farms rents out the hectares which are not longer used for fodder production as it seems not economically attractive to change the feed composition per cow (grassland under cultivation lowered by 40%). Indeed, the only exemptions from the linear reduction are emissions stemming from manure storage, which are rather constant in case of the actBased indicator. Obviously, the existing manure storage is a binding constraint, but an expansion by new investments too expensive.

Contrary to the farm management under the actBased constrained farm, the left hand side of figures 5 illustrates the fundamentally different abatement path under the NBased indicator. Up to about 18% reductions in GHGs, the farm almost entirely abates via reduction of GHGs from manure storage: it first uses straw cover and latter the far more expensive foil coverage to reduce CH_4 and N_2O emissions from the slurry tank. Beyond that point, the abatement strategy is almost equal to the one under the activity based indicator: herd sizes are reduced accompanied by a proportional adjustment in land use. The reduction from manure management is by far stronger than the herd size adjustments: higher N_2O emissions from manure applied to pasture allow reductions by switching from grazing to mowing.

A perhaps astonishing finding is the fact that enteric fermentation is reduced more than the lower dairy herd suggests. That is linked to the fact that the farm has to abate GHGs in average over the planning horizon. By reducing the herd size much stronger towards the end of the planning horizon, it can achieve an over-proportional reduction in replacement needs. For higher reduction levels, no heifers are kept for the last 4-5 years and cows leave the herd after their maximal number of lactations without being replaced.

The results hence underline that abatement strategy are clearly depending on the indicator. Thus, despite almost identical GHGs abated (both reduce from about 280 t to 167 t CO_2-equ. year^{-1}) when measured with the more accurate NBased indicator, significant differences in abatement costs can be expected between the indicators.

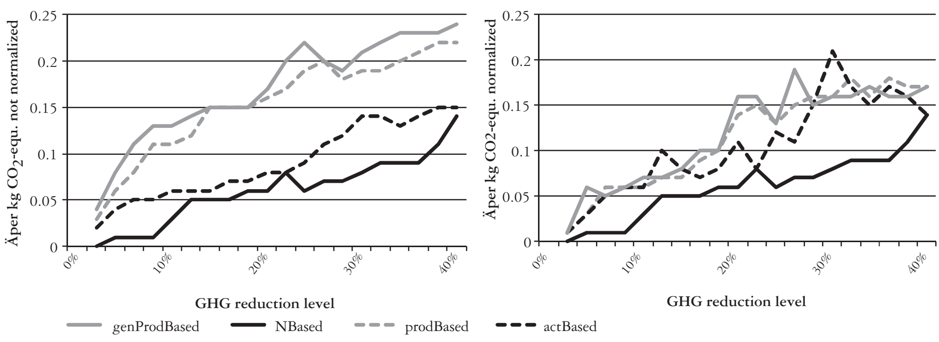
8.3. MACs under different indicators

Either way, achieving abatement of GHG emissions will cause costs on farm level or reduce overall profits of the farm as GHG ceilings acts as restrictions. Figure 6 shows the MAC curves under the different emission indicators. The left hand side shows the MACs, which drive the abatement strategies, i.e. the ones under the indicator used to define the emission ceiling (see equation 2.1. for the definition). As to be expected, the NBased indicator creates the lowest MACs for all reduction steps by offering the largest sets of abatement possibilities. The abatement cost for one unit of additional emission abatement range from 0 to 140 €/t CO_2-equ. The actBased MACs are much higher up to a reduction level of around 8% compared to the NBased one, which abates in that range by using straw cover on the slurry tank, which is rather cheap. The two curves then come closer as the NBased indicator is switching to foil cover, which is far more expensive.

Figure 6 underlines that the not normalized marginal abatement costs for the prodBased and genProdBased indicator are almost identical, but generally much higher compared to the actBased and NBased MAC curves. As mentioned above, the 5000 l cow receives a kind of discount under the actBased indicator as the emitted GHGs per animal are overestimated.

These MAC curves on the left hand side of figure 6 are the relevant ones for decisions at farm level as they drive the abatement strategies. But the simpler indicators might over- or underestimate the real abated GHGs compared to the more

Figure 6. **Not normalized and normalized MAC curves for 60 cows initial herd, 5000 kg milk head^{-1} year^{-1} initial yield potential [€/kg CO_2-equ.]**



(own calculation and illustration)

complex and accurate NBased one, and consequently, also provide biased results for the profit foregone per "real" GHGs abated. That can be clearly seen from the right hand side where the normalized abatement costs are shown according to equation 2.2.

The NBased indicator as our most accurate accounting scheme is used as the reference indicator and for normalization of MACs (equation 2.2). Hence, the normalized MAC curve for the NBased indicator is identical to the one on the left hand side. Comparing the normalized MACs on the right hand side and the ones on the left hand side shows if the indicators account for more or less GHG abated in relation to the indicator used for normalization. Imagine we used the prodBased indicator to steer abatement effort of farmers, but know that the true GHGs relevant for the climate warming effect of dairy farms can be measured with the NBased indicator. The curves suggest that if farmers abate a certain percentage of GHGs measured by the prodBased indicator, they have effectively abated less "true" GHGs. So in order to judge how expensive it was to abate the GHGs from a public good perspective, we relate the "true" change in the externality to the costs faced by the farmers. Thus, if the normalized MACs are higher than the not normalized ones, the indicator scheme overestimates GHG reductions and underestimates the real abatement costs and vice versa.

The first point to note is that the two production based indicators overestimate the "true" abatement costs, i.e. the farms abate in reality more GHGs than the indicator used to define the emission ceilings suggests. The opposite effect is found in case of the actBased indicator for wider parts of its normalized MAC curve: the "discount" in form of higher emissions per cow leads to overestimation of the abated GHGs.

We conclude that the normalization of the MAC curves of different indicators is necessary to draw correct conclusion regarding indicator recommendations. The not normalized MACs of the genProdBased and prodBased indicators signal high marginal costs at all reduction levels and would suggest implementing rather the actBased indicator, which has the additional advantage of being simpler. The normalization shows however that the actBased indicator overestimates the abated GHGs and is economically less effective. But nevertheless, both types of MACs are important for analysis: The not normalized ones show the profit losses incurred to farms by imposing an emission ceiling based on a specific indicator. The normalized MAC curves are relevant from a societal point of view to check if the indicator sends the right economic signals to the agents when GHGs are accounted based on the best available indicator.

8.4. MACs depending on farm attributes

Finally, we turn our attention to the question to what extent farm characteristics such as size or milk yield impact abatement costs, using the normalized MACs. In order to show the effect of farm attributes on the abatement costs, the profit loss for the total reduction of 40% is divided by the related reduction in GHGs when measured with the NBased indicator to derive average normalized mitigation costs per kg of CO_2-equivalent as shown in table 2.

It is obvious that all three simpler indicators lead to much higher average abatement costs compared to the NBased one. A 90 cow farm with 7000 litre cows could almost halve the abatement costs if the NBased instead of the actBased indicator is used.

A marked result is that the NBased indicator induces the lowest average abatement costs per kg CO_2-equ. (always below 100 €/t) independent of farm characteristics. But for all indicators, average abatement costs per kg differ depending on the starting herd size as well as on intensity level.

Table 2. **Average normalized abatement cost by farm characteristics and emission indicator [€ per kg CO_2-equ.]**

Initial herd		actBased	prodBased	genProdBased	NBased
60 cows	5000 liter	0.10	0.11	0.11	0.06
	7000 liter	0.14	0.15	0.15	0.08
90 cows	5000 liter	0.12	0.13	0.13	0.09
	7000 liter	0.09	0.10	0.10	0.05

Source: Own calculation and illustration

8.5. Sensitivity experiment for manure handling

A sensitivity analysis was done for the 60 cow farm with initial yield level of 5000 kg in order to highlight the effect of sunk costs on the abatement strategy. In the runs depicted above, it is assumed that the farm owned already a simple manure barrel; a switch to other application techniques would require additional investments. The sensitivity analysis is based on an alternative assumption: manure spreading is based on contract work, allowing to flexibly switching between application types.

Under the NBased indicator which is the only one accounting for changes in application techniques, distinct differences in manure application management are noticeable and shown in table 3.

Table 3. **Share of manure by application type, contract work compared to investments in application machinery (%)**

		GHG reduction level (%)				
		0	10	20	30	40
contract work	broad spread	2.0	2.5	25.1	39.3	76.6
	drag hose	98.0	97.5	74.9	60.7	23.4
investment	broad spread	100.0	100.0	100.0	100.0	100.0

Source: Own calculation and illustration

Under the sunk cost case, new investments in an injector or a drag hose are always too expensive and manure is always broad spread. If manure spreading is based on contract work, the farms will in the baseline use the drag hose option: it reduces ammonia losses and thus saves synthetic fertilizer. The injector option would reduce losses further, but is too expensive. Under the GHG emission ceiling, it is cheaper to waste some N as ammonia instead of carrying abatement costs linked to higher N_2O losses when manure instead of synthetic fertilizer is used on pasture.

8.6. Conclusions from result section

Based on these illustrative results, preliminary statements can be made concerning the hypotheses formulated at the end of section 5. As clearly shown above by figure 6 and table 2, the shape and level of MAC curves depend on the initial farm characteristics as well as on the chosen GHG indicator. Furthermore, the MACs increase in abatement levels, which is plausible provided that the decision maker always chooses the next cost efficient abatement option. Consequently, the overall AC rise with higher emission reductions as well. The abatement costs are within the range of results from other studies. De Cara *et al.* (2005) derive maximum MACs of 20 €/t CO_2-equ for different European farm types under a 3.9% emission reduction, our results for a reduction level of 4% to baseline lead to marginal abatement costs of 10 to 60 €/t depending on the chosen indicator scheme for the example farms. Pérez and Britz (2003) come up with average marginal abatement costs of 53 €/t for a EU wide 10% reduction of agricultural emissions using the CAPRI modelling system. Our model derives MACs between 30 and 60 €/t for a ten percent GHG reduction (*cf.* figure 6). Hence, the above stated model results are within ranges of scientific findings from other studies. However, the reader should keep in mind that studies mentioned above derive costs for larger farm aggregates whereas our results only represent single example farms.

The results also underline that abatement strategies depend on the indicator as shown in figure 4 and discussed based on the emission sources shown in figure 5. With regard to the economic efficiency of different indicators and abatement strategies based on the normalized MACs (described in section 5), the NBased indicator (here taken as the reference indicator) shows the highest level of economic efficiency in abating GHGs from dairy farms. It however also requires measuring and controlling *e.g.* manure application quantities by spreading technique, which might be expensive or even impossible.

Our sensitivity experiment underlines the importance of sunk costs for the abatement strategies and motivates the application of a dynamic simulation framework over a longer optimization horizon to capture investment based options additionally to more flexible mitigation possibilities.

8.7. Expected results after model completion

Further steps will complete and expand the model template, apply it to much more farms, expand the planning horizon, perform sensitivity analysis and finally, derive aggregate results for German dairy farms. Especially the addition of a more elaborate list of GHG abatement options (*e.g.* feed additives, changes in feed digestibility) will refine the analysis regarding the normalization of GHGs and might help to find economic effective abatement strategies. Statistical analysis will reveal the relation between farm attributes and MACs, and help to derive aggregate regional and sector wide MAC curves.

8.8. Policy conclusions

The still illustrative applications do not yet allow for immediate policy recommendations. But even the preliminary results underline the key role of an appropriate indicator choice: marginal abatement costs differ considerably between indicators while differences between GHGs estimated based on "state of the art" calculations and those estimated with simpler indicators can be substantial. The notion of "better" for an indicator has at least three interlinked dimensions: *(i)* the accuracy in measuring emissions, *(ii)* its ability to trigger cost minimal abatement strategies, and *(iii)* the implementation and monitoring costs (not discussed above).

There is clearly more analysis needed which also takes monitoring costs and the administrative burden for farmers into account. Assume, to use a hypothetical example, that analysis would reveal that strategies under a complex, very hard to actually implement and control indicator with low MACs do not differ across farms. All farmers would choose the same easy to observe strategy such as an investment in foil silo coverage to reduce GHGs in a cost effective way. One might conclude that the most efficient policy is to enforce the strategy on all farms rather than to implement economic instruments based on a GHG indicator scheme, which would only lead to additional private and public costs related to its implementation on each farm on top of the actual abatement costs.

9. Conclusion

The paper discussed the structure and application of a farm-specific economic simulation model for German dairy farms, which is able to cover a great variety of GHG abatement options and to derive farm specific marginal abatement cost curves for different emission indicators. We argued that a fully dynamic model integrating binary and integer variables is necessary to analyze GHG abatements in dairy farms. Illustrative model results showed that the model template creates robust and economically reasonable reactions to emission ceilings, that the choice of emission indicator has a significant impact on abatement costs and that abatement strategies as well as MACs depend on farm attributes such as herd size or milk yield. Our findings underline that the choice of emission indicator is indeed a core question in environmental policy design as simpler, more aggregate indicator schemes can lead to quite biased results.

Further research is necessary to improve the indicators, include more abatement options in the model template and apply it systematically to farms with different attributes to allow scaling up to sector level. Equally, a final evaluation of indicators will require taking also control and implementation costs into account.

References

Bates J. (2001) *Economic Evaluation of Emission Reductions of Nitrous Oxides and Methane in Agriculture in the EU – Bottom-up Analysis*, AEA Technology Environment and National Technical University of Athens, Culham, Abingdon, 90 p.

BMELV (2010) EU-Agrarpolitik nach 2013 – Plädoyer für eine neue Politik für Ernährung, Landwirtschaft und ländliche Räume, Gutachten vom Wissenschaftlichen Beirat für Agrarpolitik beim Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz, *www.bmelv.de/beirat_agrarpolitik_gutachten* (stand: 15.12.2010).

Boadi D., Benchaar C., Chiquette J. and Masse D. (2004) Mitigation strategies to reduce enteric methane emissions from dairy cows: Update review, *Canadian Journal of Animal Science* 84, 319–335.

Boeckx P., Van Cleemput O. (2001) Estimates of N2O and CH4 fluxes from agricultural lands in various regions in Europe, *Nutr Cycl Agroecosyst* 60, 35-47.

Breen J.P. (2008) Simulating a market for tradable greenhouse gas emissions permits amongst Irish farmers, 82nd Annual Conference of the Agricultural Economics Society, Royal Agricultural College, 31st March to 2nd April, Rural Economy Research Centre, Teagasc, Athenry, Ireland.

Britz W. (2011) The graphical user interface for CAPRI version 2011, Technical paper, University Bonn, *http://www.capri-model.org/docs/Gui2011.pdf*.

Dämmgen U. (2009) Calculations of emission from German agriculture – National emission inventory report (NIR) 2009 for 2007, Landbauforschung vTI Agriculture and Forestry Research, Sonderheft 324, Braunschweig, Germany.

De Cara S., Houzé M. and Jayet P.-A. (2005) Methane and nitrous oxide emissions from agriculture in the EU: A spatial assessment of sources and abatement costs, *Environmental & Resource Economics* 32, 551-583.

De Cara S., Jayet P.-A. (2006) Mitigation of greenhouse gas emissions in EU agriculture: An assessment of the costs of reducing agricultural emissions and enhancing carbon sinks in agricultural soils, INSEA Report SSP1-CT-2003-503614-Final, European Commission, INSEA, IIASA, Laxenburg, Austria.

De Cara S., Jayet P.-A. (2001) Agriculture and climate change in the European Union: Greenhouse gas emissions and abatement costs, AAEA Annual Meeting, August 4-8, Chicago.

De Cara S., Jayet P.-A. (2000) Emissions of greenhouse gases from agriculture: The heterogeneity of abatement costs in France, *European Revue of Agricultural Economics* 27 (3), 281-303.

Durandeau S., Gabrielle B., Godard C., Jayet P.-A. and Le Bas C. (2010) Coupling biophysical and micro-economic models to assess the effect of mitigation measures on greenhouse gas emissions from agriculture, *Climate Change* 98 (1-2), 51-73.

FAO (2010) Greenhouse gas emissions from the dairy sector – A life cycle assessment, Food and Agriculture Organization of the United Nations, Animal Production and Health Division, Rome, Italy.

FAO (2009) The state of food and agriculture – Livestock in the balance, Food and Agricultural Organization, Rome, Italy.

Flachowsky G., Brade W. (2007) Potenziale zur Reduzierung der Methan-Emissionen bei Wiederkäuern, *Züchtungskunde* 79 (6), 417-465.

Guan H., Wittenberg K.M., Ominski K.H. and Krause D.O. (2006) Efficacy of ionophores in cattle diets for mitigation of enteric methane, *Journal of Animal Sci*ences 84, 1886-1906.

Hediger W. (2006) Modeling GHG emissions and carbon sequestration in Swiss agriculture: An integrated economic approach, *International Congress Series* 1293, 86-95.

Huirne R.B.M., Dijkhuizen A.A., Van Beek P. and Hendriks T.H.B. (1993) Stochastic dynamic programming to support sow replacement decisions, *European Journal of Operational Research* 67, 161-171.

IBM (2011) IBM ILOG CPLEX Optimizer, High-performance mathematical programming solver for linear programming, mixed integer programming, and quadratic programming, *http://www-01.ibm.com/software/integration/optimiza-tion/cplex-optimizer/*.

IPCC (2007) Climate change 2007- Synthesis report, Contribution of Working Groups I, II and III to the Fourth Assessment, Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 104 p.

IPCC (2006) *IPCC Guidelines for National Greenhouse Gas Inventories*, prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds), IGES, Japan.

Jentsch W., Schweigel M., Weissbach F., Scholze H., Pitraft W. and Derno M. (2007) Methane production in cattle calculated by the nutrient composition in the diet, *Arch. Anim. Nutr.* 61, 10-19.

Johnson J.M.F., Franzluebbers A.J., Lachnit Weyers S. and Reicosky D.C. (2007) Agricultural opportunities to mitigate greenhouse gas emissions, *Environmental Pollution* 150, 107-124.

Kamra D.N., Agrawal N. and Chandhary L.C. (2006) Inhibition of ruminal methanogenesis by tropical plants containing secondary compounds, *International Congress Series* 1293, 156-163.

Kennedy J.O.S. (1987) Principles of dynamic optimization in resource management, *Agricultural Economics* 2, 57-72.

KTBL (2010) *Betriebsplanung Landwirtschaft 2010/2011, Daten für die Betriebsplanung in der Landwirtschaft* 22, Auflage. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt, 784 p.

KTBL (2008) *Betriebsplanung Landwirtschaft 2008/2009, Daten für die Betriebsplanung in der Landwirtschaft* 21, Auflage. Kuratorium für Technik und Bauwesen in der Landwirtschaft, Darmstadt, 752 p.

KTBL (2002) *Emissionen der Tierhaltung. Grundlagen, Wirkungen, Minderungsmaßnahmen.* KTBL/UBA Symposium, *KTBL-Schrift* 406, Darmstadt, 374 p.

McGinn S.M., Beauchemin K.A., Coates T. and Colombatto D. (2004) Methane emissions from beef cattle: Effects of monesin, sunflower oil, enzymes, yeast, and fumaric acid, *Journal of Animal Sciences* 82, 3346-3356.

Nemhauser G., Wolsey J. (1999) *Integer and Combinatorial Optimization,* Wiley-Interscience series in discrete mathematics and optimization, New York, Wiley-Interscience Publication, 784 p.

Osterburg B. (2004) The problem of incomplete information and impacts on strategies for the abatement of greenhouse gas emissions from agriculture, *in: Greenhouse Gas Emissions from Agriculture, Mitigation Options and Strategies,* Weiske A. (ed.), International conference organized by Institute for Energy and Environment, Leipzig, Germany, 209-215.

Osterburg B., Nieberg H., Rüter S., Isermeyer F., Haenel H.D., Hahne J., Krentler J.G., Paulsen H.M., Schuchardt F., Schweinle J. and Weinland P. (2009) Erfassung, Bewertung und Minderung von Treibhausgasemissionen des deutschen Agrar- und Ernährungssektors, Studie im Auftrag des Bundesministeriums für Ernährung, Landwirtschaft und Verbraucherschutz, Paper provided by Johann Heinrich von Thünen-Institut - Federal Research Institute for Rural Areas, Forestry and Fisheries in its series *Arbeitsberichte aus der vTI-Agrarökonomie with number* 03/2009, Braunschweig.

Pérez I., Britz W. (2010) Greenhouse gas emission trading in European agriculture: A comparison of different policy implementation options in year 2020, Contributed Paper at the IATRC Public Trade Policy Research and Analysis Symposium "Climate Change in World Agriculture: Mitigation, Adaptation, Trade and Food Security", June 27-29, Universität Hohenheim, Stuttgart, Germany.

Pérez I., Britz W. (2003) Reduction of global warming emissions in the European agriculture through a tradable permit system. An Analysis with the Regional Agricultural Model CAPRI, *Schriften der Gesellschaft für Wirtschafts- und Sozialwissenschaften des Landbaus e.V.* 39, 283-290.

Pérez I., Britz W. and Wieck C. (2003) Modeling of passive environmental indicators for the European agriculture: The role of marginal abatement costs, Paper presented at the 12th Annual Conference of the European Association of Environmental and Resource Economics *(EAERE)*, Bilbao, Spain.

Pérez I., Holm-Müller K. (2007) Opt-in of the agricultural sector to the European trading scheme for greenhouse gas emissions. A proposal and its possible effects, *Agrarwirtschaft* 56 (8), 354-365.

Pochet Y., Wolsey L.A. (2006) *Production Planning by Mixed Integer Programming,* Springer Series in Operation Research and Financial Engineering, Springer Science + Business Media, USA, 499 p.

Rausser G.C., Hochman E. (1979) *Dynamic Agricultural Systems: Economic Prediction and Control. (Dynamic Economics: theory and applications),* volume 3, North Holland, New York and Oxford, Elsevier Science Ltd, 380 p.

Rosenthal R.E. (2010) *GAMS – A User Guide*, Washington DC, GAMS Development Corporation, 261 p.

Smith P., Martino D., Cai Z., Gwary D., Janzen H., Kumar P., McCarl B., Ogle S., O'Mara F., Rice C., Scholes B., Sirotenko O., Howden M., McAllister T., Pan G., Romanenkov V., Schneider U. and Towprayoon S. (2007) Policy and technological constraints to implementation of greenhouse gas mitigation options in agriculture, *Agriculture, Ecosystems & Environment* 118 (1-4), 6-28.

Steinfield H., Gerber P., Wassenaar T., Castel V. and Rosales M. (2006) *Livestock´s long shadow – environmental issues and options*, Food and Agricultural Organization FAO, Rome, Italy, 390 p.

UBA (2009) Nationaler Inventarbericht zum Deutschen Treibhausgasinventar 1990-2007, Berichterstattung der Klimarahmenkonvention der Vereinten Nationen und dem Kyoto-Protokoll 2009, *Climate Change* 02/09.

UNFCCC (2008) Challenges and opportunities for mitigation in the agricultural sector, Technical paper FCCC/TP/2008/8, *http://unfccc.int/resource/docs/2008/tp/08.pdf* (stand 10.03.2011).

Velthof G.L., Oenema O. (1997) Nitrous oxide emissions from dairy farming systems in The Netherlands, *Netherlands Journal of Agricultural Science* 45, 347-360.

Vermont B., De Cara S. (2010) How costly is mitigation of non-CO_2 greenhouse gas emissions from agriculture? A meta-analyses, *Ecological Economics* 69 (7), 1373-1386.

Weiske A. (2006) Selection and specification of technical and management-based greenhouse gas mitigation measures in agricultural production for modelling, Specific targeted research project n°SSPE-CT-2004-503604, MEACAP WP3 D10a.

Weiske A., Michel J. (2007) Greenhouse gas emissions and mitigation costs of selected mitigation measures in agricultural production, Specific targeted research project n°SSPE-CT-2004-503604, MEACAP WP3 D15a.