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Up to date relevant GHG abatement options in German agricultural dairy production systems

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Abstract

Mitigation of greenhouse gases is receiving more and more interest in current political discussion and also in the agricultural context. This technical paper comprises a summary and categorization of different applicable greenhouse gas mitigation options discussed in the literature that are able to effectively reduce GHG emissions arising from dairy production facilities in Germany. GHG mitigation options are therefore identified which have great differences in time resolution with regard to their implementation and practical applicability as well as effects on the relevant gases (CH_4, N_2O, CO_2). Further on costs induced by mitigation strategies show different uncertainties concerning sensitivities to farm exogenous impacts.

Keywords: *GHG mitigation, greenhouse gases, GHG abatement options*

 Developed during the work on a DFG-funded project (HO 3780/2-1).

1 Categorization of abatement options

This working paper was developed during the work on the DFG-funded project “The Relation Between Indicators for the Crediting of Emission Rights and Abatement Costs – A Systematic Modelling Approach for Dairy Farms” (DFG reference: HO 3780/2-1). The summarized results of this work were obtained during the construction of a farm-level model approach for German dairy farms[1] analysing GHG mitigation options that have to be implemented in the model. In the following only mitigation options that are applicable up to now and allowed in Germany and the European area are considered and explained.

So far, there are several abatement options for the mitigation of methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions that are discussed in the literature on agricultural production and for the dairy sector in particular. SMITH et al. (2008: p. 790) classify the mitigation of emissions into reduction (e.g. through better C and N efficiency and fodder optimization), enhancement (accumulating C in soil), and avoidance of emissions (replacing, for example, production requiring high energy with more extensive production). Admittedly, the approaches that best mitigate emissions depend on many conditions and thus vary between regions, farm sizes, and production orientations. So there are great differences concerning the practical feasibility of the mitigation options. From an application-oriented point of view a mitigation option can mean employment or adaption of existing technologies (e.g. change of milk yield potential, fodder composition, or N-fertilizer intensity) or involvement of new technologies (e.g. new type of manure storage, feed additives like oils, new manure application techniques). Furthermore, we want to use a fully dynamic framework as our general modelling approach considers a long planning horizon to be able to consider developments and production decisions that are connected with long term investments. Because of this we also have to consider the time resolution and the impact of abatement options on the possible development paths of the firms. Referring to this, we can classify mitigation possibilities into two general groups, *permanent* and *temporal*:

Permanent options (fixed/discrete/irreversible)

Permanent abatement options are mainly characterized by investment decisions or management changes which influence the production process for a longer period, not allowing for a

[1] Named DAIRYDYN (LENGERS and BRITZ, 2012)

flexible adjustment over time (e.g. from month to month or from one year to another). So emissions are reduced indefinitely compared with the situation without usage of the permanent option. Options include, for example, coverage of manure storage, choice of specific floor conditions in the stable, decisions about the general stable type (slatted floor, deep litter, slurry, etc.) and size, animal-keeping system, or different manure storage and application techniques which are discrete in time but influence possible future decision paths. This is a special attribute of permanent options, leading to path dependencies. The decisions for permanent options are 0-1 decisions (binary variables), whereas the amount of their implementation is of integer character as they can only be implemented as a whole. Once applied, a reversal of the options in the next years would cause sunk costs and perhaps extra costs of uninstalling or replacement of the basic structure of buildings or machines. The mitigation effect of the single options can be fixed as a specific total amount or a percentage reduction compared to the situation without the option. The costs that occur due to the specific permanent mitigation options can be easily derived from the investment cost of the single option (costs calculated as depreciation cost over useful lifetime or operating hours).

Temporal options (variable/continuous/reversible)

This type of abatement option facilitates a flexible adjustment of the decision maker facing new conditions or constraints. The abatement strategies that are summarized under this category are more reversible or temporal than the permanent options. Allowing the farmer more flexible reactions from year to year or from month to month is the main advantage of these options. Also the temporal pattern of influence on the GHGs may be different among mitigation options. Some of the variable options involve new technologies (like fodder additives) but are also highly flexible in usage over time. But the majority of variable options are presented by changes to existing production processes and techniques, which are not added to the production process like new types of manure application but are implemented endogenously in the dairy production process. Examples are fodder optimization or improvement of fertilizer use, which can influence the emission of GHGs. Variable options allow for a dynamic adjustment of the farmer’s decision variables which influence, for example, breeding activities, herd size management, fertilizer intensity, fodder optimization processes, and the choice of fodder ingredients. It is obvious that most of these decision variables influencing the flexible mitigation strategies are continuous variables which can be varied in the scope of the side conditions (e.g. minimum dry matter, maximum fodder). Mitigation effects of these process-based options are calculated through emission functions concerning ruminant fermentation or manure-handling processes depending on the flexible decision variables of the farm. The costs of GHG abatement are calculated directly from the implementation cost or indirectly through a change of variables in the dairy production process. When the cost of inputs and the amount of output and revenues change, the economic development of each farm related to the change in calculated GHG emissions will show the mitigation costs caused by the abatement strategies.

1.1 Description of mitigation options

In the following sections, relevant mitigation options for the German or European dairy context are named and described, referring to several up to date works in the literature (e.g. BOADI et al., 2004, FLACHOWSKY and BRADE, 2007; KTBL, 2002; OENEMA et al., 2001; OSTERBURG et al., 2009a; 2009b; SCHILS et al., 2006; VABITSCH et al., 2004: p. 197; WEISKE, 2005). The list of mitigation options might appear relatively restricted and short, and a subject-specific reader may know of additional GHG abatement strategies (like those listed in the SAC-Report by MORAN et al., 2008: p. 148, for example). But, as mentioned before, only mitigation options that are practically applicable within the tight system boundaries of the modelled dairy farms are to be considered. Therefore qualitative valuations like those from OSTERBURG et al. (2009a: pp. 41) concerning practicability, efficiency, and uncertainty are used. Furthermore, abatement options which are operative following several research results but in conflict with German or European law are excluded from the examination (like for example addition of types of antibiotics to the ration).

1.1.1 Permanent options

Stable type

The animal-keeping system in the stable has a significant role concerning emission rates of methane and nitrous oxide as shown for example by an overview of HARTUNG (2002: pp. 195–196). Emissions in the stable are determined by floor conditions as well as aeration rates and by whether the stable has a solid or slatted floor, slurry based or deep litter systems, and tied or free stalls. Additionally, the question of whether the herd spends 365 days in the stable or if pasture is also available for the animals has to be taken into account. But pasture management is in turn a variable option which can in principle be combined with all of the different stable types as long as grazing areas are available. As shown by the table below, the choice of stable type with its specific floor conditions can have a meaningful impact on the GHG emission amounts. But decisions on stable types are not reversible or flexible so that in an existing enterprise this management or control option will only be considered if replacement or expansion investments take place.

Table 1: CH_4 and N_2O Emissions from dairy stable systems in grams per livestock unit[2] and day

(Following HARTUNG, 2002: pp. 195–196)

system:	CH4	author	N2O	author
dairy in tied stall	327	Kinsman et al., 1995	0.14-1.19	Amon et al. 1998
	120	Groot Koerkamp and Uenk, 1997		
	194	Amon et al., 1998		
dairy in free stall	320	Sneath et al., 1997	0.8	Sneath et al., 1997
	265	Groot Koerkamp and Uenk, 1997	0.3-2.9	Brose, 2000
	267-390	Seipelt, 1999		
	200-250	Brose, 2000		
dairy deep litter	782	Seipelt, 1999	2.01	Amon et al. 1998

As shown by the table and stated in CHADWICK and JARVIS (2004: p. 72), slurry based systems have lower nitrous oxide emissions from animal housing and storages because of their more anaerobic milieu. That there is little or no emission of nitrous oxide due to slurry-based stable systems is also underlined by the findings of THORMAN et al. (2003), who found 4–5 mg of N_2O-N m²/d emissions from cattle housed with straw bedding. Following this, a change from straw-based systems to slurry-based systems can be valued as a meaningful N_2O mitigation option. But, in turn, storing animal excreta under anaerobic conditions in, for example, sub-floor pits can boost CH_4 production from the managed manure. The effect of different floor conditions in the case of solid or slatted floor is not clearly identifiable up to now. For example SCHNEIDER et al. (2005) and ZHANG et al. (2005) state that on average solid floors cause slightly higher methane emissions in free stalls compared with slatted floors. Contrary to that, SNELL et al. (2003) quantified lower CH_4 emissions for solid floor conditions. In the case of N_2O emissions SCHNEIDER et al. measure higher emissions from slatted floors, while ZHANG et al. on the contrary found lower nitrous oxide measurements for slatted floors.[3]

Manure storage techniques

CH_4 and N_2O are emitted during the storage of manure and dung outside the stable. The emission rates depend on the total deposition quantity of the animals, storage time, and the addi-

[2] One livestock unit is equivalent to 500 kg live weight.

[3] For a tabulated listing of emission measurements given in the literature see also SCHIEFLER and BÜSCHER (2011: p. 158).

tional substances that allow a conversion into GHGs (for example, straw is added to deep litter systems). The feed quality and ingredients, feeding techniques, animal type, and milk output level have a measurable influence on the control of gaseous emissions from manure storages in particular. (CLEMENS et al., 2002: p. 203) But these factors belong to mitigation techniques based on feeding and intensity management, which are discussed in later sections. As an external factor which is not controllable from the farm side, environmental aspects such as temperature and condensation rates are also important. With a proper choice of storage techniques one has the possibility to react to given environmental location factors as well as to manure attributes induced by feeding practices.

For liquid manure storage, we can assume two different types, lagoons and silos (surface liquid manure reservoir), among which the silo variant can be identified as the dominant one for the German context and general gaseous activities in both systems can be assumed to be equal. Concerning the surface of the liquid manure, different possibilities exist. Manure without a layer of scum is anaerobic (except for the upper 1–1.2 cm), so the potential for nitrous oxide emissions is near zero (CLEMENS et al., 2002: p. 204). But on the other hand this is the perfect condition for CH_4 accumulation. Especially for cattle slurry, the formation of a layer of scum is possible because of the high content of organic matter, which increases the risk of N_2O emissions. Additionally, artificial coverage options exist for liquid manure, like finely chopped straw. This option is mainly adopted to reduce ammonium but it can yield N_2O emissions because of the aerobic processes in the covering layer. Conflicting statements exist in the literature concerning the effect of straw coverage on CH_4 emission rates. (CLEMENS et al., 2002: p. 204) SOMMER et al. (2000) state that methane emissions would diminish by 38% on average. Contrary to this, HARTUNG and MONTENEY (2000) and WULF et al. (2002: p. 488) mention an increase in CH_4 quantities, which could be explained by the addition of carbon to the slurry. Straw cover as well as slurry aeration is also identified as having a negative overall environmental effect by the analysis of AMON et al. (2004: p. 95). As an additional and most effective control technique, foil coverage is mentioned, which enables a totally airproofed closure of the storage to reduce CH_4 and N_2O emissions. Technical degrees of efficiency of between 80% and 100% can be assumed for this mitigation option (KRENTLER, 1999, cited in OSTERBURG et al., 2009a: p. 64). Further possibilities exist with regard to the handling of liquid slurry. Separation of manure, for example, avoids the production of N_2O from the liquid compound because a layer of scum cannot build up (CLEMENS et al., 2002: p. 205; OSTERBURG et al., 2009a: p. 64).

Storage techniques for dung do not show such variety. Following CLEMENS et al. (2002: p. 208) this type of animal excretion emits mainly N_2O. The rate of aeration of stored dung seems to be very relevant for the emission amounts, whereas N_2O and CH_4 emissions can be diminished significantly through largely aerobic storage, which means a high technical input is required for loosening, comminuting, and moving the material.

The costs that are connected with different storage techniques arise mainly from the building and installation costs. Partly, additional requirements for machinery or labour input can arise through such GHG mitigation options.

Application technique

With regard to the amount of GHG emission that is controllable by application techniques, in general the exogenous factors that influence the processes are the same as those that affect the storage techniques. Temperature, soil attributes, general consistence and N content of the manure that has to be recovered are important and exogenously given or not controllable by the choice of application technique. Further on, application quantity and time markedly impact the occurrence of GHGs. (CHADWICK et al., 2011) The application technique is relevant not only for the liquid manure or dung that is produced by the dairy farm but also for the handling of fertilizers. Following CLEMENS et al. (2002: pp. 210–212), broad spreading, trail hose, and injection are the most relevant application techniques for liquid manure. But with regard to research results of GHG emission impacts of the different slurry application techniques, CLEMENS et al. (2002: p. 211) mention great differences in the emission effects that occur and DITTERT et al. (2001) underline that injection can result in increasing N_2O emissions. Nevertheless, there are also authors who quantify the mitigation potential of application techniques as to be negligible (OSTERBURG et al., 2009a: p. 72). (The option of adapting a proper application technique for manure can in certain cases also belong to the variable or temporal options if for example the extraction of organic as well as synthetic fertilizers is handled by external enterprises. In this case a flexible change between application techniques is possible without producing sunk cost due to earlier investments in machinery.) Nevertheless, there is also a possibility to implement different application techniques as temporal options if contract work is allowed. This is normally more expensive per kilogram of fertilizer applied in comparison to private mechanization (calculated over the full depreciation time and high capacity utilization), but leads to more flexibility and less sunk cost in the case of changes of application type over short intervals.

1.1.2 Variable/temporal options

Fodder optimization

Dairy production leads to specific requirement functions for forage and feed with regard to lactating cows, heifers, and calves. These requirements have to be fulfilled by the fodder composition. Improving the quality and nutrition significantly reduces the methane production per animal (holding output constant) and per unit of product. The optimization of fodder ingredients and feed composition enhances the animal performance and means that a higher fraction of the fodder energy is converted to useful sinks (e.g. weight gain, milk output, productive lifetime, body condition). Furthermore the digestibility of fodder ingredients plays a significant role as higher digestibility lowers methane production, so for a low-emitting fodder composition only compounds with high digestibility rates are relevant (HELLEBRAND and MUNACK, 1995). (O´MARA, 2004) This optimization of the feed conversion efficiency can lead to substitutions of roughage with concentrates (BATES, 2001: p. 42). Overall it can be assumed that the minimum or maximum requirements of the animals arising from maintenance and activity should be fulfilled optimally so that no energy or nutrient overhang exists which would lead to higher emissions of N_2O or CH_4 from the manure. Additionally the feed conversion efficiency is very important. As also mentioned by BOADI et al. (2004: p. 323) and JOHNSON et al. (1996) the fermentation of cell wall carbohydrates influences methane production. Concerning the energy source of concentrates less CH_4 is emitted by starch in the ration compared to the fermentation of soluble sugars, so substituting sugar with starch in the ration (concentrate) is meant to diminish methane emissions significantly (JOHNSON et al., 1996; MILLS et al., 2001: pp. 1591–1593). The main factors of the fodder ingredients which influence the occurrence of emissions from enteric fermentation are also described precisely in MONTENY et al. (2006: p. 164), for example.

Breeding activities/replacement rates

“The most promising approach for reducing methane emissions from livestock is by improving the productivity and efficiency of livestock production, through better nutrition and genetics” (ERG, 2008: p. 4). Herds consist of animals with different genetic potential. With selective breeding activities the farmer can influence the overall milk yield potential of the farm’s livestock or even breed low-emitting phenotypes. Raising the milk output per cow through more sharp selection decreases the amount of methane emitted per kilogram of milk because emissions that arise from energy requirements for maintenance are spread over a larger output

(CAPPER et al., 2009: pp. 2163–2165; ERG, 2008: p. 4; MONTENY et al., 2006: p. 165). Conditional upon the increasing milk yield potential of the cows, also emissions per cow are typically higher because of higher food intake. But as the productivity of each cow increases, the farm manager can reduce the herd size to produce the same amount of output (ERG, 2008: p. 8). This aspect is also discussed by FLACHOWSKY and BRADE (2007: p. 440) and CORRÉ and OENEMA (1998), who name the increase of yield level as the most efficient option to abate methane emissions from ruminant fermentation so far. In addition to the genetic characteristics, breeding and selection activities can yield a higher longevity of the animals, which will decrease methane emissions from the herd (O´MARA, 2004). The longer each lactating animal stays in the herd, the fewer calves and heifers are needed for replacement and reproduction, which results in lower total methane emissions because of a lower total amount of livestock. Thus controlling the useful lifetime and hence the number of lactations per cow has a meaningful impact on methane emissions (FLACHOWSKY and BRADE, 2007: pp. 441–442). But generally one can say that there exists a trade-off between breeding for higher milk yield and increasing the longevity of the animals, because a higher proficiency level of cows is attended by a reduction of their expected useful lifetime. In addition, the output curve of each cow influences her economically efficient useful lifetime and thus the replacement rates. The decline of the milk output of each cow in later lactation phases also affects the emissions that occur per kilogram of output. So, beside an economically efficient useful lifetime, an emission-efficient number of lactation periods can also be derived for each cow. Hence, changes of the replacement rate are an applicable management-oriented abatement strategy in dairy production (WEISKE et al., 2004: p. 140).

Intensity management

Increasing the production intensity means that the output per production unit is raised. For arable production this means that input levels of fertilizer and pesticides will be heightened and optimized to reach a higher yield level per hectare. The more intensive animal production is to raise output level per animal and per stable place, the higher is the input level of nutrients, labour, investments, and perhaps veterinary costs. A higher intensity level, through for example higher rates of concentrate, normally causes higher emissions of N_2O and CH_4, overall and per production unit. But depending on the relation between the emissions that originate from nutrient inputs, fertilizer, or manure storage/application and the production output quantities, intensity management can be an option to diminish emission quantities per unit of product (BATES, 2001: p. 39; OSTERBURG et al., 2009a: p. 54). So, increasing productivity decreases emissions per product unit (kilogram of milk) (JOHNSON et al. 1996). This effect of CH_4 reduction per kilogram of milk with increasing intensity level can be illustrated by the research results of FLACHOWSKY and BRADE, shown in the following figure.

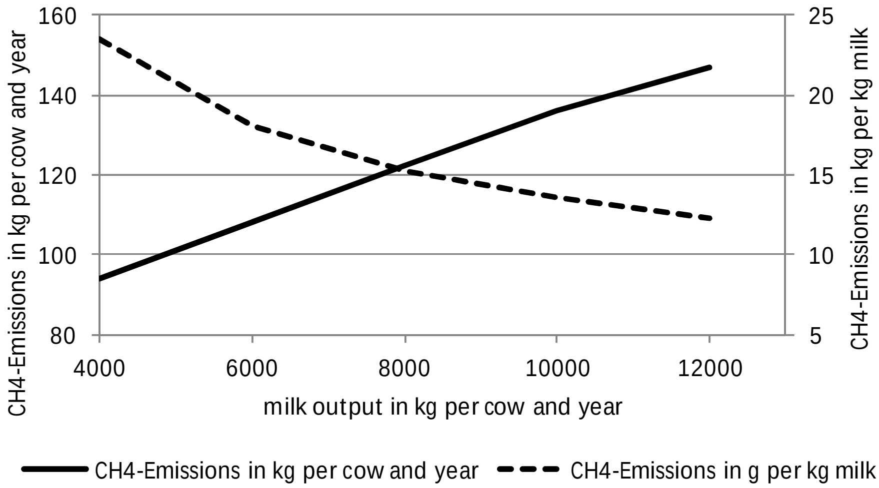

Figure 1: CH_4-emissions by fermentation process in the rumen

(Author's own illustration following FLACHOWSKY and BRADE, 2007: p. 438)

To reach higher milk yields, the fodder intake has to be increased. With higher milk output levels, nutrient requirements also go up. But as the dry matter intake (DMI) capacity of cows is restricted, the energy concentration per kilogram of DMI has to be increased. This can normally only be achieved with higher concentrate rates in the fodder, which leads to a higher DMI intake per day and a higher level of milk yield. As shown by the figure above, this means an increase in CH_4 emissions per cow but diminishing emissions per kilogram of product. (LOVETT et al., 2005) This can for example be explained by the results of MILLS et al. (2001: pp. 1590–1591) and JOHNSON and JOHNSON (1995), who determine that increasing the DMI of cows diminishes the proportion of gross energy lost as CH_4. So the concentrate to roughage ratio has to be aligned with the maximum DMI to provide the energy which is necessary to achieve a desired level of milk yield. Also, KIRCHGESSNER et al. (1995) show that an increase of milk output quantity per cow from 5000 to 10000 kg per year increases the methane production per animal by 23% but reduces CH_4 production per kilogram of milk by 40%. As already mentioned in relation to the option of breeding for higher genetic milk yield potential, increasing single-animal efficiency also reduces GHG emissions per animal through optimal intensity management. A drawback of this option is that an increase in intensity level to fully utilize the milk yield potential of the cows will lead to a decline of their useful lifetime, with fewer lactation periods, and hence animal replacement rate increases, which leads to a higher demand for calves and heifers (a bigger animal population means more GHG emissions). But, following FLACHOWSKY and BRADE (2007: p. 440), increasing the intensity level and thus the output per production unit can be named as the most effective option for mitigating CH_4 emissions so far.

Increasing the milk yield can also impact the gaseous emissions of nitrous oxide, as nitrate content in the manure is a source of N_2O emissions and higher milk yield levels diminish the N content in excreta per kilogram of milk output (KIRCHGESSNER et al., 1991a). This is described in CLEMENS and AHLGRIMM (2001: p. 291) using N-excreta functions from KIRCHGESSNER et al. (1993). This circumstance can be a result of asymptotically diminishing excreta amounts per kilogram of milk output with increasing milk yield level as shown by WINDISCH et al. (1991). These authors derived interesting linear relationships between feed intake, milk yield level, and resulting excreta amounts, where the relationship between daily feed intake in kilogram of dry matter and the amount of manure occurring is calculated as 2.4 + 2.88 * (kg DMI/day) = (kg manure). The formula depending on daily milk output was derived as 2.6 + 0.92 * (kg milk/day) = (kg manure). (WINDISCH et al., 1991) The factor of 0.92 shows an underproportional increase in excreta with increasing milk output level which supports the asymptotical decline in excreta amounts per kilogram of milk output as mentioned before.

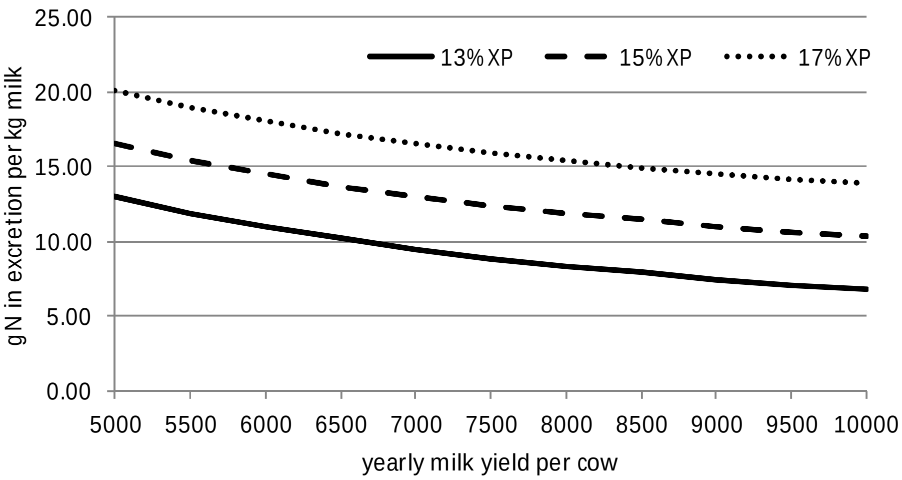

Figure 2: Nitrate content in excreta per kilogram of milk output **(XP = crude protein content in fodder)**

(Author's own calculation and illustration following KIRCHGESSNER et al., 1993)

Following the information of the above figure, keeping the overall milk production of a farm constant and increasing milk output per cow increases the milk produced per units nitrogen (N) in excreta and thus lowers the potential of N_2O emissions per kilogram of milk. Furthermore, controlling the crude protein content (XP) of the fodder composition influences the N excretion rates significantly. For example the N excretion per kilogram of milk of a cow with yearly milk output of 7000 kg increases by 80% when the XP content is increased from 13% to 17%.

This intensification effect on the emissions per kilogram of product is also true for arable production. By increasing yield levels per hectare, N_2O background emissions occurring from soils are allocated to more output and hence overall nitrous oxide emissions per product unit will diminish with increasing per hectare yields. So for example optimizing fertilizer use to reach higher yield levels is named as an effective mitigation option by BURNEY et al. (2010).

N-reduced feeding

The reduction of protein in the fodder, which is tailored to requirements of the feedstock, reduces the amount of N excreted. This causes lower GHG emissions (N_2O) from manure in the stable and from storage and N_2O emissions stemming from manure application. (OSTERBURG et al., 2009a: p. 50) This requires an N-adjusted feeding strategy in line with the animal requirements because nutrition combined with animal performance affects the N excretion (WEISKE and MICHEL, 2007: p. 9). Hence, improving N use efficiency and reducing overall N input into the system is a meaningful measure to reduce N_2O emissions as well as the overall risk of N losses (AARTS et al., 2000).

Fertilizer practice

A reduction of exogenous mineral and organic fertilizer (e.g. ammonia and urea) purchased by farms in arable production leads to lower N_2O emissions. Fertilizer management is an important regulating tool where oversupply of nitrate from fertilizer is to be avoided. This means a fertilizer adjustment is to be applied in line with demand, and thus the application amount and time have to fit the soil conditions and the yield-related requirement of the plant growth. The lower the oversupply of fertilizer, the lower is the emission potential. A further important point to mention is that fertilizer practice has to be harmonized with the application of farm fertilizer from animal production because both provide nitrogen. (OSTERBURG et al., 2009a: p. 56) CH_4 emissions are not affected by N fertilizer practice (VELTHOF et al., 2002: p. 506).

Soil cultivation

Generally one has to differentiate between arable farm land and continuous grassland (mostly pasture). With regard to these two general types of soil usages, the issue of whether or not ploughing up of continuous grassland is allowed is important because when pasture is ploughed fractions of soil carbon are transformed into CO_2. In the process, nitrate is also released as N_2O. Hence, avoiding a change in use of continuous pasture abates potential CO_2 and N_2O emissions. (OSTERBURG et al., 2009a: p. 44) Consequentially this is a kind of general assumption with regard to whether or not ploughing of continuous pasture is admissible. For cultivation of arable farmland it is also possible to change the method of husbandry. Reduction of soil cultivation, addition of organic matter, and change of crop rotation are possibilities to increase the carbon content of the soil (OSTERBURG et al., 2009a: p. 58). Further on, deposition of CH_4 is possible for grass and arable land but differs with regard to level (DÄMMGEN, 2009: p. 315).

The costs of these management strategies are composed of operating costs and different influences on market revenues for the yields obtained as well as on production costs due to substitution of fodder components with, for example, concentrates.

Herd size management/crop-growing decisions in farming

This management option is on the one hand the simplest emission mitigation option but on the other hand most likely the most expensive. By lowering the herd size the farmer decreases the possible number of emitters on the farm. But concerning the mitigation cost it is obvious that with the removal of a single cow the farm loses the gross margin of this lactating cow. So this option is meant to be an expensive way of mitigating GHG gases. Similarly a reduction of one hectare of a cash crop mitigates the emissions that are produced by the crop growing but also results in the loss of its gross margin.

Feed additives/fat content

There are different types of feed additives mentioned in the literature. The Eastern Research Group (ERG, 2008: pp. 6–7) describes the mitigation effect of feed supplementation with fats, oils, propionate precursors, and secondary metabolites. These applications influence the metabolic fermentation processes and the methane emissions that occur. According to MURPHY et al. (1995) and ASHES et al. (1997) the addition of fats and oils leads to a higher energy density of diets, raises the milk yield, and enriches the fat content of the milk. Furthermore research results show that fats and oils reduce CH_4 production (DONG et al., 1997;

MACHMULLER and KREUZER, 1999; JORDAN et al., 2004: pp. 124–130) but are also meant to have only a short term influence because of the adaption of methanogenic bacteria in the rumen to the new fodder components (ERG, 2008: p. 6). GRAINGER and BEAUCHEMIN (2011) derived a diminishing effect of higher dietary fat content on the enteric methane production per kilogram of dry matter intake, visualized in Figure 3. But the results of previous studies only stem from short term experiments and DUGMORE (2005) mentions that the feed content of fats and oils should not exceed 8% of feed dry matter. But nevertheless, digestibility is affected by higher fat contents.

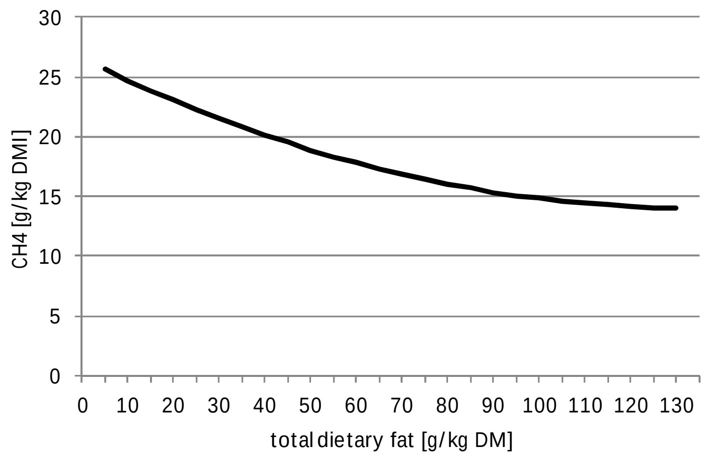

Figure 3: Methane emissions per kilogram of dry matter intake depending on dietary fat content

(Author's own calculation and illustration following GRAINGER and BEAUCHEMIN, 2011: p. 310)

Propionate precursors convey the production of propionate instead of methane from the transformation process of hydrogen in the rumen (O´MARA, 2004). But according to O´MARA the precursors are currently very expensive and their effects are not yet quantifiable in sufficient detail to be implemented into the model approach of this work. Secondary metabolites like saponins and tannins are other options for methane reduction from metabolic fermentation through inhibiting the corrosion of organic components (PEN et al., 2006). Furthermore the addition of ionophores, a kind of antibiotic, is also discussed in the literature (BOADI et al., 2004: p. 326). But as the addition of antibiotics as fodder components has been banned by European law since 2006 [Enactment (EG) No. 1831/2003] and according to JOHNSON and JOHNSON (1995) the mitigation effects are not long-lasting, this option is not of relevance for this work.

Pasture management/increased grazing

Adequate management of grazing can lead to lower overall emissions by the herd. The addition of pasture in the ration can diminish the gas fluxes of CH_4 per kilogram of DMI and per kilogram of raw product as shown in the following figure.

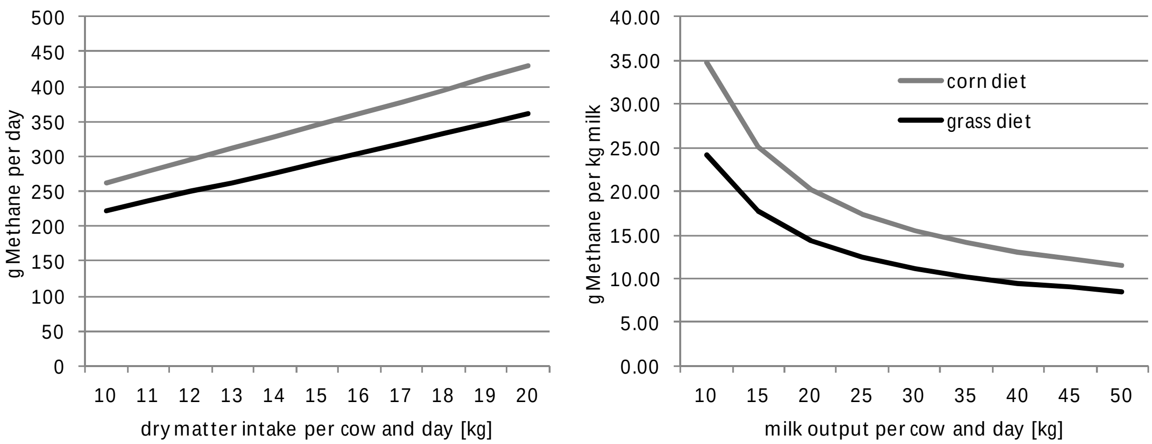

Figure 4: Methane emissions by dairy cows with a maize- and herbage-based feeding strategy

(Author's own calculation and illustration following KIRCHGESSNER et al., 1991b: pp. 93–96)

The rotation rate among pastures influences the availability of higher quality pasture for the animals, which directly impacts the productivity and decreases methane emissions per unit of product from enteric fermentation (BOADI et al., 2004: p. 325; MCCAUGHEY et al., 1997). The analysis performed by MCCAUGHEY et al. also demonstrated that there is a significant difference in CH_4 emission rates depending on whether pastures are rotationally or permanently grazed, and a 9% lower methane production per hectare per day was measured on rotationally used pastures compared to continuous grazing. Furthermore the use of pasture diminishes emissions from manure storage (because there is less manure in storage systems) but increases N_2O emissions from deposition by grazing animals (CHADWICK and JARVIS, 2004: p. 72). Comparable results are derived by VELTHOF et al. (2002) using the MITERRA-DSS model, showing that with a higher grazing portion N_2O also increases but methane emissions decrease. But also in the case of fertilizer practice on croplands, tailoring nutrient additions to pasture plant uptake reduces N_2O emissions (FOLLETT et al., 2001). Furthermore, DURU et al. (2007: p. 208) mention that an increase in N-use efficiency by controlling the grazing rates and times to guarantee a balanced herbage growth to N ratio in line with feed intake by grazing animals helps to reduce the risk of N losses. But it is important that sufficient pasture areas are available near to the farm to allow an optimal and adequate inclusion of pasture strategies in the feeding plan of the farm (OSTERBURG et al., 2009a: p. 53). This circumstance is primary dependent on the geographic region in which specific dairy farms are located. In 2009, about 40% of the German dairy livestock had access to pasture, with slight variations depending on farm herd sizes (STATISTISCHES BUNDESAMT, 2010). Hence it is an important abatement possibility that is appropriate for a large part of the German dairy livestock population. As for normal in-stable feeding, a higher pasture rate also requires an adapted addition of concentrate to regulate the milk yield level to make the best use of the CH_4 mitigation potential (FLACHOWSKY and BRADE, 2007: p. 444).

1.2 Impact of mitigation options

Summing up the above stated influences of the abatement options on emissions of CO_2, N_2O and CH_4, the following table lists the described GHG mitigation options and illustrates which gases can be influenced by the single abatement strategies; these findings are comparable with results of SMITH et al. (2008: p. 791).

Table 2: Influence of abatement options on different GHGs

(Author's own table)

	CH_4	N_2O	CO_2
permanent			
stable type	x	x	
manure management techniques	x	x	
application techniques		x	
temporal			
fodder optimization	x	x	
breeding activities	x		
intensity management	x	x	
N-reduced feeding		x	
fertilizer practice		x	
soil cultivation		x	x
herd size managment, crop growing decisions	x	x	x
feed additives/ fat content	x		
pasture management/ increase grazing	x	x	x

As visualized by the table above, many of the different abatement strategies affect the emission rates of not just one specific gas but two or even all three of the relevant GHGs. Attention to this matter it is important because some options can cause the emission rates of different gases to develop in opposite directions (ROBERTSON and GRACE, 2004: p. 61; SCHNEIDER and MCCARL, 2005: p. 9). If for example the manure management is changed towards low emission rates of methane through building up aerobic conditions in manure storage, this change will boost the outgassing of nitrous oxide, which has a much higher global warming potential (21 for CH_4 and 310 for N_2O). This fact underlines the importance of paying attention to these interactions and trade-offs between different management strategies and emission types.

Furthermore, it was mentioned that the aim of the underlying model approach is to simulate mitigation activities of a great variety of different dairy farms. Regarding this, it is important to underline that mitigation practices that do a good job of reducing GHGs on one specific dairy farm type may be less effective when farm characteristics are different (SMITH et al., 2008: p. 798). Thus it is very important to build up a highly disaggregated and detailed model application to incorporate this farm-specific abatement effectiveness and efficiency of mitigation strategies depending on structural farm conditions. Not being able to offer a universal list of mitigation options to all farms, the proposed practices have to be selected and adjusted to each individual agricultural production system on the farm.

So far, there are several studies dealing inter alia with the level of mitigation potential of different abatement options (e.g. SMITH et al., 2008: p. 802). These allow for a relative ordering (ordinal scale) of the mitigation options with respect to their abatement capacities. Obviously, here the abatement potential is enlightened from an engineering point of view. The inclusion of economic aspects in addition may lead to totally different results by also recognizing farm-dependent cost efficiencies of different mitigation strategies.

2 Sensitivity of different mitigation options

As mentioned before, the main aim of this work is to derive cost functions in dairy production which occur through GHG-abating adjustments of the production process on individual farms. Because of this, the costs associated with the use of each single option are very important for the derivation of abatement and marginal abatement costs for GHGs. But as several mitigation options like milk yield intensity management or fertilizer practice have an impact on production levels, the mitigation costs that occur through diminishing production amounts are directly linked to the market price of milk and cash crops (e.g. slaughtering of a cow as a GHG-mitigation option becomes more expensive when milk prices are high because one loses the whole gross margin of the cow; in the case of low milk prices the economic loss is not as great). So the mitigation costs can vary significantly, depending on actual and future market prices (which are denoted as exogenous variables by the model definition of a supply side model without market feedbacks). These price sensitivities of mitigation options can be identified as price-related barriers of implementation and application of the mitigation strategies because they may be coupled with a high price risk. In the light of a planning horizon over several periods, the price risks of different options can have significant differences when comparing permanent options (not allowing for reaction when prices change) with temporal mitigation options (which allow a flexible adjustment or change in reaction to price changes which impact the cost of the abatement strategy).

In contrast to that, other options like different stable types or manure application and storage techniques are not as sensitive to market prices. Prices that influence the mitigation costs of these options are only the prices for investment in the year of installation. The amortizations of these investments per year quantify the associated costs that are combined with the abatement caused by the mitigation options (plus possible interest payments for investment credits). Regarding this, a slight limitation has to be considered, because investment-based techniques can also lead to indirect costs induced by differences in N loss rates by different storage or application types.

Hence, different mitigation options have different levels of sensitivity to external changes. So they have different uncertainties. This has to be implemented in a proper decision framework for the choice of farm-level abatement strategies, which is also mentioned by SCHILS et al. (2005: p. 174), who state that “the uncertainty itself should be used as one of the selection criteria for mitigation options”.

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