SIXTH FRAMEWORK PROGRAMME
PRIORITY 8: Policy-Oriented Research

SPECIFIC TARGETED RESEARCH PROJECT n°SSPE-CT-2004-503604

Impact of Environmental Agreements on the CAP

Document number: MEACAP WP3 D7a
Dissemination level: public

Survey of technical and management-based mitigation measures in agriculture

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Date: June 2005

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Glossary

AAFC	Agriculture and Agri-Food Canada
AD	Anaerobic Digestion
AI	Artificial Insemination
AN	Ammonium Nitrate
BST	Bovine SomatoTropin
CAN	Calcium Ammonium Nitrate
CDM	Clean Development Mechanism
CE	Cost effectiveness
DNA	DeoxyriboNucleic Acid
ECCP	European Climate Change Programme
ESE	Environmental Side Effect
GHG	GreenHouse Gas
GIS	Geographical Information System
GMO	Genetically Modified Organism
GPS	Global Positioning System
GWP	Global Warming Potential
IGER	Institute of Grassland and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LCA	Life Cycle Assessment
LECA	Light Expanded Clay Aggregates
LU	Livestock Unit
MCFA	Medium-Chain Fatty Acid
MP	Mitigation Potential
NSC	Non Structural Carbohydrate
NUE	Nitrogen Use Efficiency
NVZ	Nitrate Vulnerable Zone
TF	Technical Feasibility
UAN	Urea/Ammonium Nitrate
UNFCCC	United Nations Framework Convention on Climate Change
VFA	Volatile Fatty Acid
WSC	Water-Soluble Carbohydrate

Introduction

It is by now widely accepted that increases in atmospheric concentrations of greenhouse gases (GHG) contribute to the process of global warming and climate change. Climate change is a global problem, affecting all countries and representing one of the gravest challenges to future sustainable development. The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), which was negotiated by more than 160 countries in 1997, called for industrial economies to reduce their collective GHG emissions to an average of 5.2 % below 1990 levels over the first commitment period (2008-2012). The European Union member states committed themselves to reduce the anthropogenic GHG emissions by 8 % in relation to the 1990 levels by 2008-2012. In order to meet the reduction targets, it is necessary to implement abatement measures for anthropogenic GHG emissions in all sectors of society, including agriculture.

The agricultural sector is likely to influence the rate and magnitude of climate change considerably, as it is both a significant source and sink of a number of greenhouse gases. Agricultural activities substantially contribute to the global net flux of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) and have a large influence on ammonia (NH_3) and nitric oxide (NO) emissions. The share of the agricultural sector in total GHG emissions is approximately 10 %, including 40 % of CH_4 and 60 % of N_2O emissions, respectively. Because of these high contributions, agriculture offers significant opportunities for GHG abatement, and substantial research efforts aim to identify and assess suitable mitigation options for CH_4, N_2O and CO_2 from agricultural sources.

Livestock and poultry farming and the use of fertilisers are key sources of GHG emissions such as N_2O emissions from arable soils and pastures, N_2O and CO_2 emissions from cultivated organic soils, CH_4 emissions from enteric fermentation as well as CH_4, N_2O and NH_3 emissions from manure management. Adaptive mitigation strategies therefore need to be identified, formulated and implemented for the agricultural sector, to enable it to both adapt to future environmental change, and to limit GHG emissions. The potential of technical mitigation measures must be evaluated regarding the emission reduction potential, environmental side-effects, technical feasibility and the specific costs, yet much of the information is still lacking.

A large number of measures for decreasing emissions from agricultural sources have been proposed. Direct soil emissions of N_2O can be mitigated by reducing nitrogen inputs to soils, e.g. by a more efficient use of manure and mineral fertiliser nitrogen in agriculture. CH_4 emissions from enteric fermentation can be controlled by increasing the rumen efficiency and by improving animal productivity. CH_4 emissions from manure management can be reduced either by prevention of anaerobic decomposition of manure or by stimulating the (controlled) fermentation of manure in digestion plants with the recovery of CH_4 which can be used for electricity and heat production. NH_3 emissions from animals can be reduced by changes in the nitrogen content of the feed, changes in manure management, or substituting urea fertiliser by ammonium nitrate.

Next to technological improvements of the production process such as manure application techniques, management-related measures also need to be investigated further. However, no single measure will be sufficient to stabilise or reduce atmospheric GHG emissions. Instead, different measures based on technological change, economic incentives, and institutional frameworks are needed that are adapted to the specific farm conditions within each region.

The assessment of emission factors and the potential of agriculture to mitigate GHG emissions has been the subject of intensive scientific investigation in recent years. Usually, mitigation options have been described separately for each greenhouse gas not taking into account their common sources or origins. As a result it is difficult to determine possible interactions between the directly active gases CO_2, CH_4, N_2O and the indirectly active greenhouse gases such as ammonia, resulting in NO and N_2O emissions.

A comprehensive analysis of mitigation measures ideally has to take all greenhouse gases, their specific formation processes and the total net effect of all GHG emissions into account, since action to mitigate GHG emissions at one point in the production chain and a saving of nutrients at the same time can lead to a higher potential of emission formation at a subsequent point of the agricultural production chain. However, the uncertainty in the estimates of emissions from the various biogenic sources is large. Additional uncertainties are linked with the reduction efficiency, cost-effectiveness, impact on environmental side-effects and the technical feasibility for the implementation of recommended measures. Therefore, it is the objective of science to provide policy makers with a reliable estimation of GHG emissions from the various agricultural sources and to describe balanced, cost-effective and feasible technical mitigation options to enable definition and implementation of measures and policies to reduce GHG emissions.

Against this background it is the aim of this study to give an overview of technically feasible measures in European agricultural production chains. The report is based on an extensive and critical literature review, data from existing studies and the knowledge of the MEACAP partners and external experts. As a first step, possible mitigation measures are listed and described in detail. These technical measures are grouped according to their emission source within the farming system (animal and plant production). Some measures have an impact on the whole farming system and some may have an even wider sphere of possible influence (e.g. management-based measures or use of fossil fuels):

- Measures related to livestock and poultry farming
  (e.g. animal housing; grassland and grazing management; feeding strategies; farmyard manure and slurry management; anaerobic digestion),
- Measures related to crop production
  (e.g. slurry, manure and mineral fertiliser management and application techniques; carbon sequestration; bioenergy crop production),
- Management-based measures,
- Use of fossil fuels.

In addition, some political instruments recently discussed in Europe are described. Next the advantages and disadvantages of each technical measure are discussed taking into account the interaction of nutrients and greenhouse gases as well as the estimated environmental side-effects and feasibility. Finally, an evaluation table is added to each measure that assesses the individual 'GHG mitigation potential', 'technical feasibility', 'environmental added value' and 'cost effectiveness' in a qualitative way. For the evaluation of the 'environmental added value' criteria such as the impact on soil compaction, soil disturbance, erosion, humus conservation, water quality (e.g. by nitrate leaching), odour and dust emissions, acidification and eutrophication were included, but the impact on landscape features and biodiversity were excluded. The 'cost effectiveness' of technical measures reflects the estimated relation of the costs for the implementation of the technical measures to their GHG mitigation potential.

1 Measures related to livestock and poultry farming

1.1 Animal breeding and husbandry

1.1.1 Livestock breeding

Details of measure:

Genetic improvement programmes are in place for all common livestock and poultry species in Europe, offering increased output from lower input costs by increased feed efficiency, reproductive efficiency, improved growth rates etc. Improving the genetic merit of dairy cows has increased in the last decade, for instance, with the import of Holstein genetic material from US and Canada for use with the EU native dairy breeds. As a result, average European yields have increased. For example, the UK dairy herd has increased its average yield by 8.8 % from 1995 to 1997 (ADAS, 1998). One of the major improvements is the ability of the cow to partition nutrients into milk preferentially to maintenance and/or growth. This has undoubtedly resulted in increased efficiency.

Thus, choice of origin and genetic set up in stockbreeding to breed livestock with higher N use efficiency or to improve individual animal performance to reduce the methane produced per unit of product can result in a significant reduction of total GHG emission in the future livestock and poultry sector.

Advantages:

The genetic merit of livestock within the EU is rapidly improving and this will undoubtedly lead to increased efficiency, and potential reductions in e.g. methane emissions.

Clark et al., 2001 reported how improving individual animal performance reduces the methane produced per unit of product. In terms of methane production, the use of a smaller number of higher genetic merit animals to produce a given amount of product would therefore be beneficial. High reductions of CH_4 are estimated by genetic improvement by Mosier et al. (1998). Less N amounts in manure are also possible by genetic merit (higher N use efficiency).

Disadvantages:

Animal breeding is only a long-term measure (EPA, 1989). However, the management of these high genetic merit livestock animals and poultry will also become more complex and overall implementation of this approach may be stalled by animal welfare implications. For example, high genetic merit cows can have increased problems with fertility, lameness, mastitis and metabolic disorders, and all these issues will have to be addressed if genetic progress is to be successfully continued.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

1.1.2 Artificial insemination

Details of measure:

Artificial insemination (AI) is a routine procedure on dairy farms and the vast majority of dairy cattle are produced in this way. AI is a process by which sperm are collected from the male, processed, stored and artificially introduced into the female reproductive tract for the purpose of conception. AI has become one of the most important techniques ever devised for the genetic improvement of farm animals. It has been most widely used for breeding dairy cattle and has made bulls of high genetic merit available to all. AI can be carried out by technicians from approved AI centres, by qualified vets or, increasingly, by licensed farmers on their own cows.

Advantages:

The greatest advantage of AI is that it makes possible maximum use of superior sires. Natural service would probably limit the use of one bull to less than 100 matings per year. In 1968, AI usage enabled one dairy sire to provide semen for more than 60,000 services.

An increase in the reproductive performance of the animals and an increase in herd reproductivity performance in order to reduce the size of pedigree cattle herds may be a measure to reduce methane release (EPA, 1999).

Superior quality offspring (bulls etc.) may be available at low cost.

Disadvantages:

The technique of inseminating a cow is a skill requiring adequate knowledge, experience and patience. Before entering into an artificial insemination programme, a producer should carefully analyse his breeding programme and goals. AI is an extremely powerful tool, but it may not be for every producer.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	→	↗

1.1.3 Planned selection of male/female at insemination (embryo and sperm sexing)

Details of measure:

Sex selection in e.g. cattle is on the road to becoming a commercial reality within the next few years. Sperm sexing is one way to control the sex of offspring. Several methods have been attempted, but the first effective one utilised cell-sorting techniques. Due to a high-speed sperm sorting instrument thousand male- or female-producing sperms can be sorted per second to select sex.

The ability to regulate the sex of an offspring is of major concern to animal producers. For example, commercial beef cattle producers generally would like male offspring as they command a higher price than females due to more rapid gain in weight. Dairy-cow owners, however, essentially prefer all females if the cows are inseminated with dairy-cattle semen.

Advantages:

Using this method to select for female calves has some benefits. Breeders in the dairy industry can achieve three important outcomes: female calves for herd replacements, female calves for milk production and female calves for trouble-free heifer calvings. Due to the controlled selection of male or female by embryo and/or sperm sexing the individual productivity can be improved so that the increase of specialisation may reduce the total GHG emissions of a farm.

Disadvantages:

There are some technical but mainly ethical problems with this procedure.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	↗

1.1.4 Twinning

Details of measure:

Twinning is the ability to have twins where most commonly the species has a single birth. Twin birth offers the potential for increased beef production efficiency if suitable changes in management can be made to accommodate problems inherent with twinning. Exploitation of twin birth presents a potential means of dramatically improving efficiency of e.g. beef production.

Advantages:

Twinning reduces the amount of GHG produced per birth and from the lactating female per offspring.
Research has shown that twinning is one way that farmers can increase their yield per e.g. calving season (beef). This will increase the income of producers due to more weight per year per cow.

Disadvantages:

Twinning may include increased incidence of calf mortality, dystocia (malpresentation), stillbirth, abortion, calf abandonment, and retained placenta, lengthened interval from parturition to conception and occurrence of freemartin heifers. Therefore, successful use of twinning in beef cattle production will require changes in management to address problems of increased dystocia and calf mortality and poorer postpartum reproduction. Key changes in management may include diagnosis of twin versus single pregnancy, modification of nutrition for cows bearing or suckling twins and use of early weaning.
Additionally, there are some ethical problems with this procedure.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	→

1.1.5 Lifetime efficiency (calves, cattle, cows / meat, milk)

Details of measure:

For dairy cows, an increase in lifetime efficiency means more lactations per cow as the number of lactations per cow (apart from the milk yield) influences the lifetime methane production. Recently, the trend is that the number of lactations per cow decreases. For beef cows there may be no additional scope. It was proposed to use milking cows to a higher extent for producing calves. This would minimise methane emissions in calf production. The use of more bulls and less steers for beef production could reduce the methane emission as well: bulls grow faster and methane emission is mainly proportional to lifetime.

Advantages:

In beef production systems, animals often go through store periods where there is little or no weight gain. This extends the time needed to reach a given slaughter weight, and increases the lifetime methane production. If efficiency could be improved, it would result in significant improvements in lifetime methane emissions. This is a technology transfer issue, but the EU has an opportunity to encourage it through judicious use of the premium system. For instance, payment of slaughter premium could be conditional on animals being under a certain age. Thus, the measure would have no additional cost.

Disadvantages:

The number of lactations per cow is falling as improving genetic merit increases milk production but brings problems with health and fertility.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	→

1.1.6 Multi use of cows (milk, calves and meat)

Details of measure:

The 'multi use of cows' is a possibility to change the trend towards specialist milk cows and specialist beef cows in comparison to a more systematised exchange of calves between dairy farms and beef farms.

Advantages:

The separation between dairy and beef production gives a higher total methane production which can be lowered by the multi use of cows (based on kg product). A combined milk and beef production also in the future would probably be a good compromise.

Disadvantages:

Specialisation and intensification separately in dairy and beef production may sometimes be more efficient to reduce total amount of GHG emissions.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

1.2 Animal housing and in-barn manure management

1.2.1 New low-emission livestock and poultry housing systems

Details of measure:

Many of the options for reducing emissions from housing described in scientific studies of the past decades can be implemented in newly built animal houses. Emissions from livestock buildings can significantly be reduced through improved design and construction of the floor (see 1.2.2.3, 1.2.3, 1.2.7, 1.2.8.2, 1.2.9, 1.2.12), ventilation (climate control) (see 1.2.2, 1.2.4) and manure management (see 1.2.3 to 1.2.12). Manure can be handled as a liquid, a slurry, a semi-solid, solid or farmyard manure. Several options for collecting and storing manure are available, depending on the manure form. Regardless of the manure form, well-designed collection, storage, transport and land application components for both liquids and solids are required for a beneficial manure management programme. Housing systems can be adopted to minimise the emitting surface area (see 1.2.7), reduce temperature (see 1.2.3) or pH of manure surface (see 1.2.13) or intake capacity of air above the manure (see 1.2.2). Planning buildings that minimise exposed surfaces may therefore reduce e.g. NH_3 emissions. Different animal housing systems have to be considered: straw-based systems (see 1.2.9.1), slurry-based systems (see 1.2.10, 1.2.12), deep litter (see 1.2.9.2) and tied systems (see 1.2.5).

Advantages:

Reduction of GHG and NH_3 emissions compared to reference systems (e.g. slatted floor; see 1.2.12). In general, tie-stall systems have less manure-exposed surfaces than loose-housing systems (see 1.2.5). New livestock and poultry housing systems may have positive influence on more hygienic production conditions as well as on animal health and welfare.

Disadvantages:

Due to high costs this measure is only applicable if new buildings are required. In contrast to NH_3, little data on the emissions of CH_4, N_2O and CO_2 from animal houses are yet available.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	→	↗

1.2.2 Ventilation

Ventilation of any air space is the volume of air being constantly replaced by new air from the outside. The factors that influence the freshness of air within a house are 1) the cubic air capacity and 2) the rate of air entry and exit.
High cubic air capacities allow for the even dissipation of aerosols, heat dust and other wastes in the air, reducing the need for a high rate of air change in the house. Therefore, the purpose of ventilation is to 1) supply oxygen rich air, 2) remove gases, odours, dust and bacteria, 3) remove the heat generated by the housed livestock making bedding areas drier and cooler and 4) remove moisture from within the house.

1.2.2.1 Natural ventilation

Details of measure:

Basic natural ventilation systems use sidewall openings or combinations of sidewall and ridge or stack openings. Natural ventilation is especially applicable for cattle and pigs. The two main ways in which natural ventilation occurs are through the stack effect in calm conditions, through combined stack effect and wind and through wind only at air speeds above 3 m sec^{-1}.

Stack Effect:
Warm air is lighter than cool air and it rises being replaced by cooler air. The movement of warm air upwards is exploited in animal houses where there is an air opening at the highest part in the roof to allow the warm air to leave the house, and openings lower down in the house allow cool air to enter the house. The stack effect is driven by the heat produced by the animals, which creates a temperature gradient between the inside and the outside. The rate of ventilation is directly proportional to the size of the openings and the height difference between inlet and outlet.

Wind Ventilation:
Almost all the ventilation design criteria are based on calm conditions. It is important to examine how the house can be made comfortable and draught free. Particularly, in calf and dairy cow housing it is essential to reduce draughts at ground level which would cause chills. The critical element which affects draughts is the internal airflow pattern established in the house. The critical design features to be looked at are 1) inlet design, 2) outlet design, 3) gable end protection and 4) roof slope and house orientation.

Advantages:

Natural ventilation reduces on-farm energy consumption, which in terms reduces GHG emissions. Rathmer et al. (2000) and Niebaum (2001) also reported a NH_3 reduction. Jungbluth et al. (2001) measured a reduction of N_2O emissions in loose housing with natural ventilation. The investment costs for new buildings with natural ventilation are very low.

Disadvantages:

To maintain high levels of productivity with natural ventilation requires proper siting, design and temperature mechanisms.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↑

1.2.2.2 Ventilation rate

Details of measure:

Many studies show that NH_3 emissions correlate significantly with air speeds (Katyal & Carter, 1989; Hoeksma et al., 1992; Cumby et al., 1995; Büscher et al., 1996). Air speeds across manure-covered surfaces should be minimised since the amount of NH_3 emitted by manure increases with air speed. The design, location and management of ventilation inlets can affect air speeds across the floor and over the pit surface.

Advantages:

Minimisation of air speeds across manure surfaces can result in a reduction of NH_3 emissions.

Disadvantages:

Only very few data are available, mainly because the gas concentrations are very low, and accurate measurement of ventilation rates in naturally ventilated houses is therefore difficult (see **Error! Reference source not found.**), time consuming, and requires extensive equipment (Hartung & Monteny, 2000).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.2.2.3 Decreasing of air velocity above manure

Details of measure:

Air speeds across manure-covered surfaces should be minimised since the amount of NH_3 emitted by manure increases with air speed (see 1.2.2.2, 1.5.1). Investigations have shown that the design, location and management of air inlets can effect air velocity around surfaces exposed to faeces and urine and thereby affect the release of ammonia. Air inlets should therefore be designed and located in such a way that they minimise air velocities above these surfaces. Most incoming air (in cold weather) should therefore travel across the ceiling first and then down to the floor.

Advantages:

Reduced NH_3 emissions due to the lower airflow over the manure surface.

Disadvantages:

Feasibility could be connected with high costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.2.3 Reducing the temperature of the manure and surfaces it covers

Details of measure:

The manure may be cooled, e.g. in the dung channels by water circulating through a system of pipes beneath the bottom of the culvert.

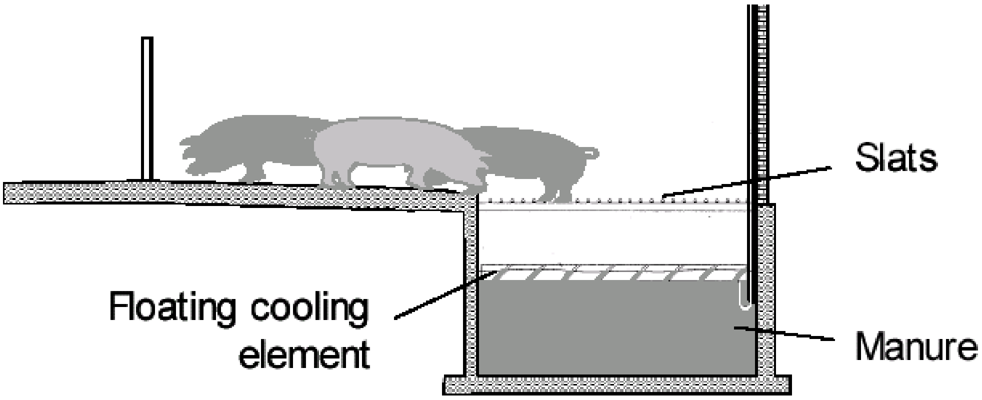


Figure 1: Schematic depiction of the housing system with a reduced emitting surface in the manure pit underneath the slatted floor (Source: Ogink & Aarnink, Wageningen, The Netherlands).

Advantages:

Cooling of manure results in the reduction of direct and indirect GHG emissions. Cooling of the surface of the manure in the under-floor pit to 12 °C or less by pumping groundwater through a floating heat exchanger can substantially reduce NH_3 emissions (Groenestein & Huis in 't Veld, 1996; UNECE, 1999).

Disadvantages:

Slurry cooling for reducing emissions from manure has been shown to be effective but would be expensive (equipment for cooling, energy costs for cooling) and would entail CO_2 emissions from fossil fuels for electricity needed. Reliable data are not available.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	↘

1.2.4 Purification of animal house emissions (filtration technologies)

Details of measure:

Elimination of odours, separation of NH_3, dust and microorganisms and reduction of greenhouse gases by biofiltration, bioscrubbing, chemical scrubbers etc. These techniques can only be applied in animal houses equipped with mechanical ventilation, which is often the case for pigs and poultry (Hahne et al., 2002; Schier & Büscher, 2004).
In biofilters and air scrubbers, NH_3 in the air is absorbed in the process water, converted into nitrite and then into nitrate.

Biofiltration:
Biofiltration is the aerobic conversion of air-borne impurities into non-polluting components (primarily CO_2, H_2O and inorganic salts). Biofiltration absorbs NH_3 in the stable air and converts it to nitrite and nitrate. The polluted gas passes through an open-bed filter consisting of biologically active material, such as compost or wood chips, and contains naturally occurring microorganisms which decompose the contaminants (Figure 2).

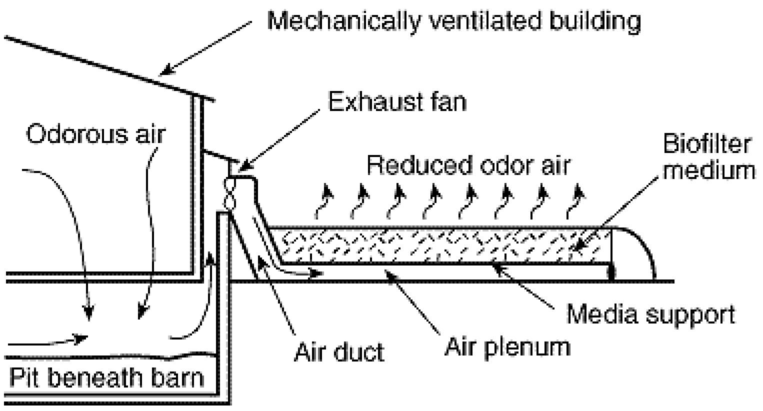


Figure 2: Passing the exhaust air from a livestock building through a biofilter (a bed of organic material, such as straw or compost) can greatly reduce odours (Source: University of Minnesota Extension Service).

Bioscrubbing:
Impurities in waste gases are absorbed by water in a scrubbing column and decomposed by microorganisms contained either in the column (trickling filter) or in a separate reservoir (activated sludge installation) to produce harmless components, primarily H_2O and CO_2. The resulting sludge must be removed in order to guarantee continuous operation. The purified water can be recirculated.

Chemical scrubbers:
In a wet scrubber, an alkali (e.g. an aqueous chlorine dioxide solution) is usually added to react with acidic pollutants.

Advantages:

Air treatment systems can remove multiple pollutants. Applying these measures can significantly reduce NH_3 emissions from housing (Klaassen, 1991).
According to Hahne & Vorlop (2004), NH_3 emissions were reduced too, whereas the N_2O emissions from denitrification increased (see *disadvantages*). Thus, net GHG emissions were only slightly reduced.
Schier & Büscher (2004) measured a dust reduction of 95 %; NH_3 was also substantially reduced. The influence on N_2O emissions was not investigated.
Biofilters are relatively economical and simple to install and maintain.
Well-designed ventilation systems which incorporate underfloor pit ventilation help reduce odour problems with these systems (see 1.2.2.3).
Sometimes this technical measure represents the only possibility to maintain the farm adjacent to residential areas (Grimm, 2005).

Disadvantages:

Due to the considerable volumes of air emitted from e.g. dairy cow buildings, some of the techniques are economically less attractive.
Bio-scrubbers require more initial capital investment (Mannebeck, 1995; Lais, 1996; Hendriks et al., 1997) and larger amounts of water than biofilters and therefore may not be practical for on-farm use. Plants for condensation or solution of the NH_3 in the exhaust air in water so far have been too expensive to be viable. Reducing methane by microbial filtration is not economical because the concentrations from animal buildings and storage tanks are too low to be effective for a controlled methane oxidation.

The ventilated air from animal houses is cleaned using nitrifying bacteria to oxidise ammonium to nitrate. This nitrification process may lead to an increase of N_2O emissions (either directly or through consecutive denitrification).

Biofiltration:

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	→

Bioscrubbing:

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↘

Chemical scrubbers:

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↓

1.2.5 Tied systems instead of loose-housing systems

Details of measure:

Instead of loose-housing to establish short-stalls (e.g. for cows 1.70-1.75 m long and 1.20 m wide) with an individually adjustable neck bow tie system and stall partitioners between each animal to guide movements in stalls, in that way preventing unnecessary contamination of the stall surfaces with faeces and urine (see 1.1.6, 1.1.9.2).

Advantages:

In general, it is agreed that this type of tying-system improves stall hygiene and reduces NH_3 emissions in stalls. A substantial NH_3 reduction seems to be possible.

Hartung & Monteny (2000) reported that CH_4 emissions from cattle houses (CH_4 emissions originate from both the animals and the excrements stored indoors) range substantially, with somewhat higher values for dairy cows in loose-housing systems (cubicle houses). This range of data is comparable with the range of CH_4 emissions used as normative values for dairy cattle in the Netherlands (Van Amstel et al., 1993). The highest CH_4 emissions occur during feeding and rumination (Brose et al., 1999). The emission levels are mainly influenced by the animal weight, the diet, and the milk yield. Furthermore, details of the housing system design (e.g. air conduction, type of flooring, type and dimensions of manure removal and storage of excrements) play an important role. The large number of influencing factors shows that realistic normative values for the calculation of CH_4 emissions (e.g. in national studies or emission inventories) should be differentiated with regard to housing systems, next to the factors which have already been stated, namely the age of the animals, the type of feed, diet and feeding level, and the lactation stage.

Amon et al. (1998) reported no difference in N_2O emissions between tethered housing with solid and liquid manure. At higher temperatures, an increase in N_2O emissions from deep litter systems was recorded. Only deep litter systems with straw seem to produce significant quantities of N_2O, which is most likely caused by nitrification and denitrification. Slurry systems, however, produce no or only little N_2O, because slurry generally contains neither

nitrate nor nitrite which could be reduced through denitrification in anaerobic areas (Hartung & Monteny, 2000; see 1.2.10).
Similar to deep litter stalls for cattle, significant N_2O emissions from pig husbandry exclusively originate from deep litter or compost systems. All pig-housing systems, however, also emit methane. Excrements temporarily stored indoors are the main source of methane emissions. The quantity of methane emitted by the animal itself should not be neglected because it may amount to up to 8 litres of CH_4 per pig and day (Ahlgrimm & Bredford, 1998). The amount of methane emitted from stalls for fattening pigs is influenced by the diet (digestibility), the daily weight increase of the animals, the air temperature, and the type of housing system (Ahlgrimm & Bredford, 1998; Hüther, 1999). With regard to CH_4, this is mainly caused by the different animal species and housing systems. Methane emissions from fattening pigs range from 1.5 to 11.1 kg per animal place per year, whereas emissions of 21.1 and 3.9 kg per animal place per year were reported for sows and weaners, respectively. Hahne et al. (1999) found higher CH_4 emissions in autumn and winter, when the air exchange rates are lower. They suggested that the CH_4 production might be influenced by the availability of oxygen over the emitting surfaces (see 1.2.2.3).
The variation in the N_2O emissions is mainly caused by the type of housing system (no data available for sows and weaners). Fattening pigs kept on partly or fully slatted floors (slurry systems; see 1.2.10, 1.2.12) emit very little N_2O, whereas higher emissions were reported for fatteners in deep litter and compost systems (Groenestein & van Faassen, 1996). At present, no reliable data are available for sows and rearing pigs.

Disadvantages:

Tied systems may cause problems of access to the feed, reduce freedom of movements and have negative influence on animal welfare. At present, loose-housing systems are more common in comparison to the tied system because of positive influence on animal health, well-being and production (especially udder and foot health are clearly linked to the stall hygiene); and these systems are expected to contribute to an increasing production of deep litter (see 1.2.9.2). In some cases deep litter systems may increase CH_4 and N_2O emissions.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

1.2.6 Cages and aviaries instead of floor systems for layer hens

Details of measure:

To establish cages and aviaries instead of floor systems for layer hens to reduce NH_3 emissions (Neser, 2001) (see 1.1.5, 1.1.9.2).

Advantages:

According to Neser (2001) and Neser & Gronauer (2002), NH_3 and N_2O emissions from cages and aviary systems compared to floor systems were substantially reduced. CH_4 emissions were not tested. This is confirmed by Hörnig et al. (2001).
Recent studies show that CH_4 and N_2O emissions from housing systems for laying hens vary greatly and must be judged very critically because the measured concentrations are very low. In general, floor husbandry systems for laying hens seem to emit more N_2O than battery cages or aviary systems, which is mainly caused by the presence of material (e.g. wood shavings, straw, litter) on the floor. Reliable CH_4 and N_2O emission data for other kinds of poultry, such as broilers, turkeys, ducks etc., and for housing systems with natural ventilation (see 1.2.2.1) are not yet available. Gas emission values for poultry are low when compared with emissions from cattle and pigs. This is mainly caused by the considerably lower body weight of the

hens. If the body weight of one laying hen is assumed to be 2.5 kg, one livestock unit (LU) would correspond to approximately 200 hens, and the N_2O emission established by Sneath et al. (1996) would amount to ca. 0.042 kg per animal per year.
The measurements of Neser (2001) confirm that seasonal differences must also be considered.

Disadvantages:

According to Groot Koerkamp (1992), aviary systems have significantly higher NH_3 emissions compared to cage systems.
For animal behaviour and health it is better to keep poultry on floor systems instead of cages and aviary.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

1.2.7 Reduction of manure contaminated surface areas

Details of measure:

Different aspects of an animal housing system for livestock and poultry, such as tied and loose-housing systems (see 1.2.5), slurry- and FYM-based system (see 1.2.5, 1.2.6, 1.2.9, 1.2.11), floor systems (see 1.2.13, 1.2.10, 1.2.12) etc., influence the manure contaminated surface area.
Factors that influence e.g. the excretory behaviour of pigs can be used to minimise the area where manure is dropped, resulting in a smaller emitting area (Hacker et al., 1994). For pig houses, the emitting surface mainly consists of the area of the slurry pit and the area of the floor wetted with urine (Figure 8, Figure 9). NH_3 increases towards the end of the fattening period and is generally higher during the summer than during the winter period (Aarnink, 1997). For the growing pigs that are housed in groups a reduction in slatted floor (see 1.2.12) and slurry pit area (see 1.2.10) will decrease the NH_3 volatilisation from the slurry pit but will increase the fouling and the volatilisation from the floor. The fouling and volatilisation of ammonia from the solid floor can be reduced by partially covering the slatted floor with studs to prevent pigs from lying in the area designated for excretion (Aarnink, 1997).

Advantages:

The research of Aarnink (1997) has resulted in facilities for growing and fattening pigs that use well climatised pens in a length/width ratio equal to or higher than 2:1 and reduce the percentage of the surface area covered with slats to 25 %. In such pens, a yearly emission of NH_3 of approx. 0.25 and 1.9 kg NH_3 per pig place and year have been found for the growth ranges from 10-25 kg and from 25-110 kg live weight, respectively, without any nutritional measures. Combinations of housing modifications and feeding strategies have also been tested for fattening pigs and show a lower emission of NH_3 than when only one factor is adapted compared to traditional systems (Van Peet-Schwering et al., 1996). According to Voermans et al. (1995), Zeeland & Verdoes (1998), Zeeland et al. (1999) and Verdoes et al. (2001), NH_3 emissions are substantially reduced through the reduction of the contaminated surface area.

Disadvantages:

The described measures may have a negative influence on animal health and welfare compared to reference systems such as loose housing or straw-based systems.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.2.8 Keeping surfaces, manure and animals dry

Maintaining bedding moisture at 20-25 % will reduce CH_4 and NH_3 losses (and odours) associated with litter or manure conditions. Preventing water contamination by adjusting the height of drinkers to avoid spillage and proper ventilation systems may help to keep animals and surfaces dry.

1.2.8.1 Improved drinking systems

Details of measure:

In the design process of feeding troughs and water drinking facilities, animal comfort and the minimisation of spilling have to be taken into account (Baxter, 1989). A simple way of maintaining dry manure (to control and reduce the moisture content of manure of all animals and surfaces of animal houses in different housing systems) is to reduce the spillage of water from drinking systems, e.g. by using a nipple system.

Advantages:

Eilwinger & Svenson (1996) showed that the use of a nipple system reduces gaseous N emissions from of the total N excretion. Dry surfaces improve the hygiene conditions.

Disadvantages:

New improved drinking systems require additional investment costs and costs for maintenance.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.2.8.2 Drying of manure

Details of measure:

NH_3 emissions from battery deep-pit or canal systems (step deck, tier; Figure 3) can be lowered by reducing the moisture content of the manure through forced or unforced ventilation over the manure pit (see 1.2.2). So-called stilt houses (where the removal of sidewalls from the lower areas used to store manure) can provide a highly effective means of ventilation.

In one Netherlands system ('floating floor system'), the litter is aerated by forcing air under the cloth ('floating') floor and the manure and litter.

The collection of manure on manure belts and the subsequent removal of manure to a covered storage outside the building can also reduce NH_3 emissions, particularly if the manure is dried on the belts through forced ventilation. The manure should be dried to a dry-matter content of 70 % to prevent the formation of NH_3. If the wastes from the manure belts are collected in an intensively ventilated drying tunnel, inside or outside the building house, the dry matter content of the manure can reach 60-80 % in less than 48 hours. In general, the emission from manure layer houses depend on a) the length of time that the manure is present on belts (long time = high emissions), b) the drying system, c) poultry breed and d) ventilation rate (low rate = high emissions).

The effect of drying poultry manure is more effective compared to pig or cattle slurry since poultry, in contrast to mammals, excrete uric acid instead of urea which is also transferred into NH_3. Related to the dry matter content, poultry manure has the highest N content with 14 kg N t^{-1} compared to 4 and 6 kg N t^{-1} in cattle and pig manure, respectively. This means that the earlier the manure is dried the less urea is transferred into NH_3.

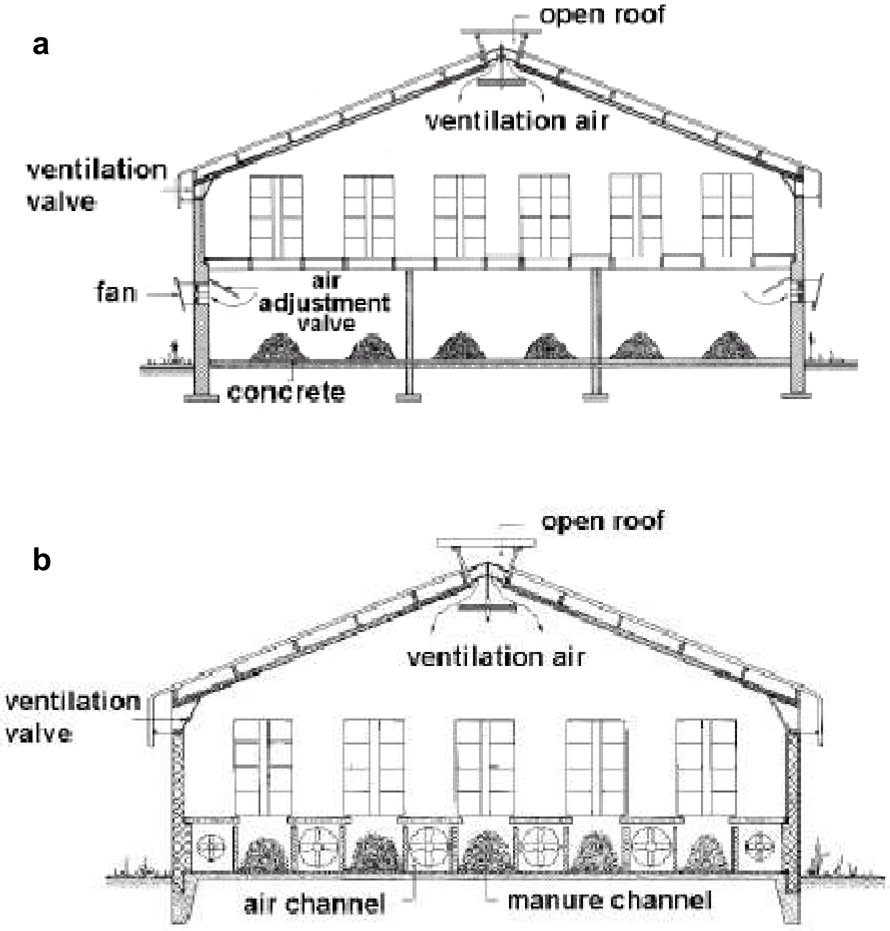


Figure 3: Deep litter system (a) and example of a canal system for laying hens (b) (Source: IPCC, 2004).

Advantages:

NH_3 emissions from housing systems for laying hens can be significantly reduced by drying of manure (either through the application of a manure belt with forced drying or by drying the manure in a tunnel) or by continuously blowing heated air under a floating slatted and littered floor to dry the litter (Klaassen, 1991). According to Najati & Van den Weghe (2000) and Gronauer (2002) a clear reduction of the NH_3 is possible. Studies of Macke & Van den Weghe (1997) showed a high emission reduction, whereas Groenestein & Montsma (1991) measured a significantly higher reduction of NH_3.
During drying, the manure tends to decompose aerobically and little or no CH_4 is produced.

Disadvantages:

This measure is very expensive and high amounts of fossil fuels are needed. The Netherlands 'floating or floating floor system' is very energy-intensive (doubles the electricity use of a conventional broiler house) and might increase dust emissions (however, the extra ventilation improves the distribution of heat, giving some savings on heating costs).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

1.2.8.3 Keeping animals clean and dry

Details of measure:

Good building hygiene reduces NH_3 emissions by reducing the amount of manure-covered surface area. This includes the animal's skin. The warm body of an animal, when covered with wet manure, provides an area of accelerated bacterial growth and ammonia production, which is quickly vaporised into the air by body heat.

Advantages:

A reduction of ammonia emissions is possible. This easy to establish technical measure is good for animal health and welfare

Disadvantages:

Cleaning of animals may increase dust.

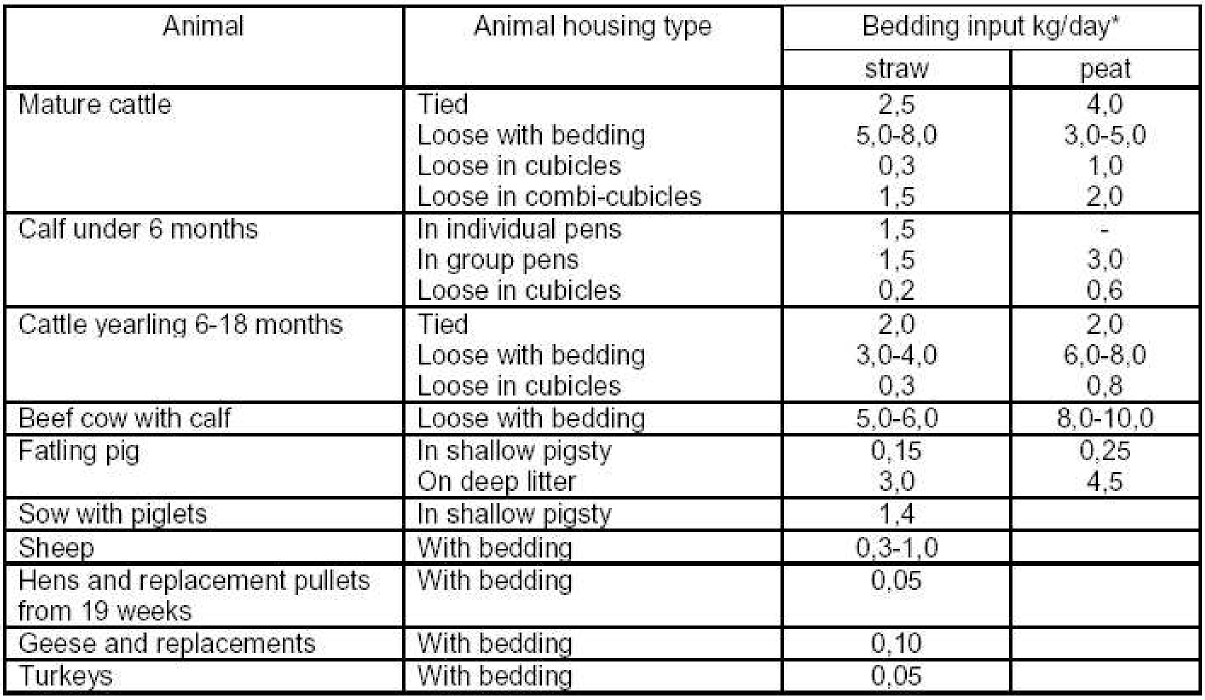
GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↑	→	↑

1.2.9 Absorption of urine / Use of bedding material

Details of measure:

Bedding is a major source of N_2O and methane. It is possible to influence the microbial activity in farmyard manure or bedding material in animal housing of cattle, pigs and poultry, e.g. by the addition of straw to solid manure to improve the C : N ratio (Enquete-Kommission, 1994) in order to reduce NH_3 emissions. Commonly-used bedding materials include various species of grain and grass straws (see 1.2.9.1; Table 1), sawdust, peat, shredded paper, reusable plastic, hardwood bark, and wood shavings (Brake et al., 1992; Thompson, 1995; White & McLeod, 1989).

Table 1: Bedding utilisation rates (Source: Šileika, 2000).



Animal	Animal housing type	Bedding input kg/day*	
		straw	peat
Mature cattle	Tied	2,5	4,0
	Loose with bedding	5,0-8,0	3,0-5,0
	Loose in cubicles	0,3	1,0
	Loose in combi-cubicles	1,5	2,0
Calf under 6 months	In individual pens	1,5	-
	In group pens	1,5	3,0
	Loose in cubicles	0,2	0,6
Cattle yearling 6-18 months	Tied	2,0	2,0
	Loose with bedding	3,0-4,0	6,0-8,0
	Loose in cubicles	0,3	0,8
Beef cow with calf	Loose with bedding	5,0-6,0	8,0-10,0
Fatling pig	In shallow pigsty	0,15	0,25
	On deep litter	3,0	4,5
Sow with piglets	In shallow pigsty	1,4	
Sheep	With bedding	0,3-1,0	
Hens and replacement pullets from 19 weeks	With bedding	0,05	
Geese and replacements	With bedding	0,10	
Turkeys	With bedding	0,05	

*Humidity of straw used for litter (15 %), humidity of peat (45 %). Rate of litter has to be increased if its humidity is higher.

Advantages:

The Dairy Housing and Equipment Handbook (1995) lists water absorption of straw at 1.05, pine sawdust at 1.25, and pine shavings at 1.0 kg of water per kg of bedding. The Dairy Manual (Adams, 1995) reports water absorption in kg of water per kg of bedding of 1.2 for chopped oat straw, 1.5 for chopped mature hay, 1.25 for pine sawdust, and 0.65-0.75 for wood shavings. Long straw is less absorbent than short or chopped straw (by a factor of 10 more). Wheat and barley straw systems combined absorb more water than barley.

A literature review in Bussink & Oenema (1998) shows that absorption of urine by straw may effectively reduce NH_3 losses. Emissions are influenced by the bedding material (straw, saw dust etc.), the amount of bedding and how often the material is applied (Van den Weghe, 2001).

Furthermore, absorbent bedding dries waste, reducing odour emission. Therefore, the addition of bedding material improves animal health and welfare. For animal welfare reasons and due to the likely increase of organic farming, straw-based systems may become more popular in the future.

It is a low cost option.

Disadvantages:

An increase of N_2O emissions due to nitrification and/or denitrification is possible. The addition of absorbent material could well augment N_2O emissions, especially in the case of using only small amounts of straw and litter, so that very wet and dense areas (anaerobic zones) may form in the litter of manure (Döhler et al., 1999). In general, N_2O emissions in the house may increase (but net total emissions from the whole manure management continuum may be lower).

Use of bedding may increase the difficulties of manure handling, so its practicality in the whole-farm system must be assessed.

More dust is found in the building with straw, and fungal spores will dominate airborne microorganisms.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.2.9.1 Straw-based systems

Details of measure:

Straw-based systems are applicable to cattle, pigs and poultry farming (see 1.2.9). For animal welfare reasons and in course of the likely increase of organic farming, straw-based systems may become more popular in the future. Ammonia emissions from straw-based housing may depend critically on the quantity of straw used: a high content can give rise to lower emissions than some traditional slurry-based housing. The amount of straw used for bedding (Table 1) for example, has an impact not only on emissions from the buildings but also on subsequent emissions during storage and spreading (Pain & Jarvis, 1999).

Advantages:

A high straw content in the manure can give rise to lower emissions than some traditional slurry-based housing (but there are currently insufficient data to prescribe specific quantities of straw per animal). For e.g. pig fattening, the NH_3 emissions of straw-based systems are substantially reduced compared to conventional slurry systems (Pain & Jarvis, 1999).

Disadvantages:

Sneath et al. (1997) identified a significant increase of N_2O emissions in their N_2O inventory for the UK. This was confirmed by Ahlgrimm et al. (1998), especially if only small amounts of litter are used. Therefore, Sneath et al. (1997) suggest as a mitigation option, changing from farmyard manure to slurry systems.

The mitigation potential in straw-based systems has so far not been fully exploited.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.2.9.2 Deep litter systems

Details of measure:

Generally, deep litter systems are applicable to cattle, pigs and poultry (see 1.1.5, 1.1.6). Deep litter group-housing systems have been developed as an alternative to intensive housing for cattle, pigs and poultry. A litter manure handling system consists of dry absorbent material (litter). In a deep litter housing system, animals are kept on a thick layer of a mixture of manure with sawdust, straw or wood shavings.

Tunnel-style (hoops)

Eco-style

Eco-shed

Conversion

Figure 4: Types of shelter for pigs (Source: H. Payne, Department of Agriculture, Western Australia).

Advantages:

Large amounts of manure are allowed to accumulate in the litter because the litter is generally removed only 1-2 times a year.

Reductions of NH_3 emissions were reported in different studies (Amon et al., 1998; Andersson, 1996; Kaiser & Van den Weghe, 1999).

Deep litter systems are positive for animal health and welfare.

Deep litter based production systems are often used because of their ease and speed of construction, high flexibility as well as their relatively low capital cost, e.g. being around one-third of the cost per pig place compared with that for conventional pig housing.

Disadvantages:

Deep litter systems for pigs should not be promoted as they are likely to result in an increase in NH_3 emissions, and as they do not offer separate dunging and lying areas, which is required by pigs (Döhler et al., 2002). According to Döhler et al. (2002), NH_3 emissions of deep litter systems for fattening bulls and heifers are also substantially higher compared to full slatted floors. Furthermore, deep litter systems tend to become too warm during summer and to release considerable N_2O emissions. Also Groenestein & van Faassen (1996) concluded that deep litter systems for fattening pigs may reduce NH_3 emissions compared with housing on fully slatted floors (see 1.2.12), but emissions of air-polluting nitrogen gases tend to be higher due to the formation of N_2O.

Amon et al. (1998) reported that deep litter systems with straw seem to produce significant quantities of N_2O, which is most likely caused by nitrification and denitrification in the litter bed. Slurry systems, however, produce no or only little N_2O because slurry generally contains neither nitrate nor nitrite (Hüther, 1999) (see 1.2.10).

Deep litter systems may also increase CH_4 emissions.

Finally, pigs in deep litter systems are fatter, have higher feed intakes and are less efficient than their conventionally reared counterparts.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↗	→	↗

1.2.10 Slurry-based systems / Deep dung channels

Details of measure:

GHG emissions from slurry are mainly caused by NH_3 and CH_4 during storage, and by N_2O losses after field application of manure (see 2.10). GHG emissions from manure management can thus be effectively abated if NH_3 and CH_4 emissions during storage (and nitrous oxide emissions after field application) are reduced.

The release of NH_3 may be reduced effectively, among other measures, by making the dung channels relatively deep, and thereby reducing the airflow above the manure (see 1.2.2.2).

Advantages:

Deep dung channels may cause reduced NH_3 emissions due to the lower air-flow over the manure surface (see 1.2.12, 1.2.2.2).

For the comparison of CH_4 and N_2O emissions of slurry- compared to straw-based systems of cattle and pigs see 1.2.5.

Disadvantages:

In new livestock buildings, this is feasible, although there may be extra costs for handling groundwater pressure and pumping of the manure. Therefore, deep dung channels are probably not a realistic measure in all locations due to ground conditions. In relation to remodelling of existing buildings, deep dung channels are considered a too expensive technique.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↘	→	↘

1.2.11 Rapid separation of faeces and urine

Details of measure:

Solid-liquid separation is a manure treatment technology that separates a portion of the solids from liquid manures of cattle and pigs, but also of poultry. Manure separation can take place in two ways: mechanical separation (active) and gravity settling (passive). Mechanical manure separation can be accomplished using a number of different means including screw presses, roller presses, and vibrating screens. In these more common technologies, the liquids of the manure pass through the screens while the solids are retained on the screen (from where it is then moved).

Vibrating screens are in the same direction with the manure stream entering the middle of the screen (Figure 5). The liquid passes through the screen openings, and the solids are taken to the edge of the screen by vibration, where they fall off. Screen separators work best with a manure stream with less than 5 % solids (Figure 6). Other separators use smaller screen sizes but press the manure through the screen, e.g. screw press, belt press or centrifuge (Figure 7). These processes can handle manure with higher content of solids and are more efficient than typical screen separators but often require more capital investment and energy input.

The products of mechanical separation are an easily handled solid and a readily pumped liquid. When manure is handled in solid form inside livestock buildings, the separation of urine from the faeces can be quite effective. The degree of separation depends to a large extent on the design of building and equipment, type of litter used and on management. Separated solids can have a solids content ranging from 12 % to 40 % (depending upon the system) compared to un-separated manure that has a typical solids content of 8 %.

Advantages:

A rapid separation of faeces and urine has a high potential to reduce NH_3 emissions. Using a mechanical separator with a mesh size of 1-3 mm lowers NH_3 losses significantly (UNECE, 1999). The separation can also reduce odours.

A better utilisation of minerals in manure could be achieved when the mineral content of a certain fraction meets the specific requirements of a certain plant production system. Separating urine and faeces is a first step to reaching these goals, supplementation of these fractions a second step and removal of certain minerals a third step to create a product that contains the right dose of nutrients and can be given according to the demand of different plants.

Higher solids content for the solids in the manure results in a more stackable and managed product that can be composted and sold (see 1.5.7), reused as bedding or feed, or more easily handled and transported to distant areas for direct application compared to un-separated manure. Separated liquids have a lower solid content compared to un-separated manure (as low as 4 %), which makes them more easily pumpable and suitable for irrigation equipment than un-separated manure. Application via irrigation equipment can be more advantageous than application via traditional manure spreaders due to more flexible application times and frequencies, less labour and less soil compaction (increased yields).

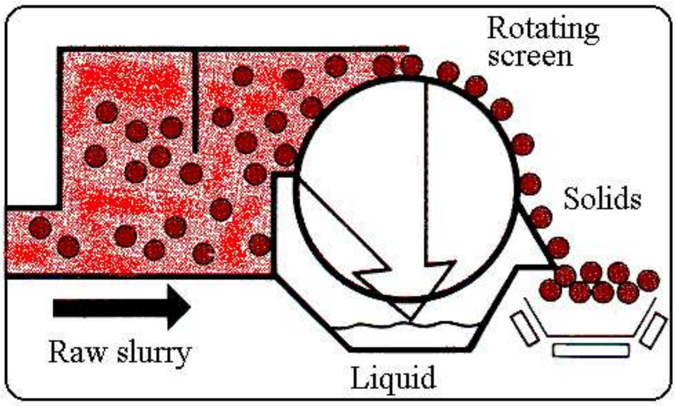


Figure 5: Vibrating screens (Source: J.R. Bicudo, University of Minnesota).

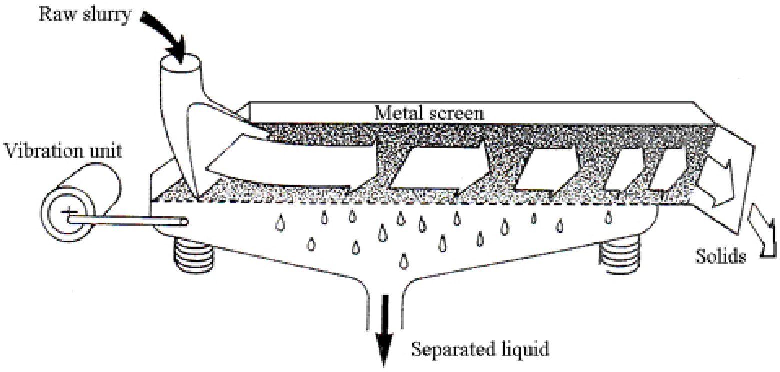


Figure 6: Screen separator (Source: J.R. Bicudo, University of Minnesota).

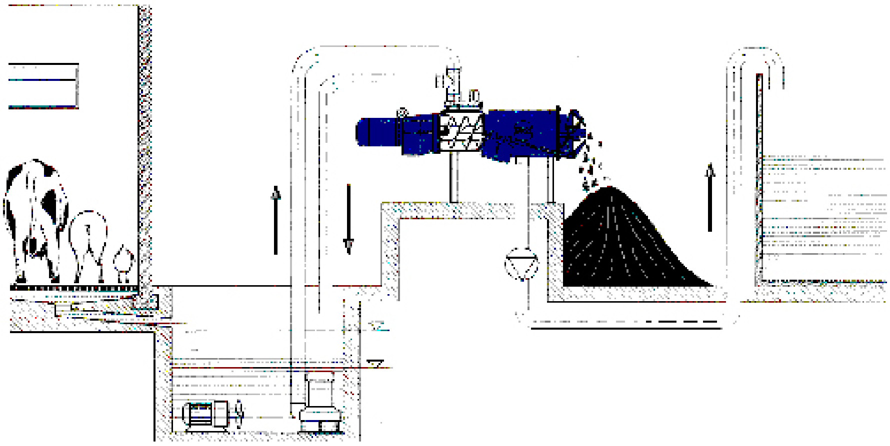


Figure 7: Separators with smaller screen sizes that squeeze manure through e.g. screw press, belt press or centrifuge (Source: J.R. Bicudo, University of Minnesota).

Disadvantages:

Resent research results show that N_2O emissions for urine and dung are generally higher than for manure application.

Additional equipment cost as well as maintenance and management requirements are needed; additional need for storage and handling of both a liquid and solid fraction.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

1.2.12 Partly or fully slatted floors

Details of measure:

Slatted floors are in very poor contact with the earth and this provides effective isolation. A slatted floor area has other benefits since a pit would help to keep the area drier and cleaner and provide a convenient place to drain urine and dung.

Advantages:

Slatted floors have the potential to reduce indirect (NH_3) and direct GHG emissions. Partly slatted floors (some 50 % area), generally give rise to lower NH_3 emissions, particularly if the slats are metal or plastic coated, allowing the manure to fall more rapidly and more completely into the pit below.

Emissions from the solid part of the floor can be reduced by using an inclined or convex, smoothly finished surface (Figure 8), by appropriate siting of the feeding and watering facilities to prevent fouling the solid areas and by good climate control.

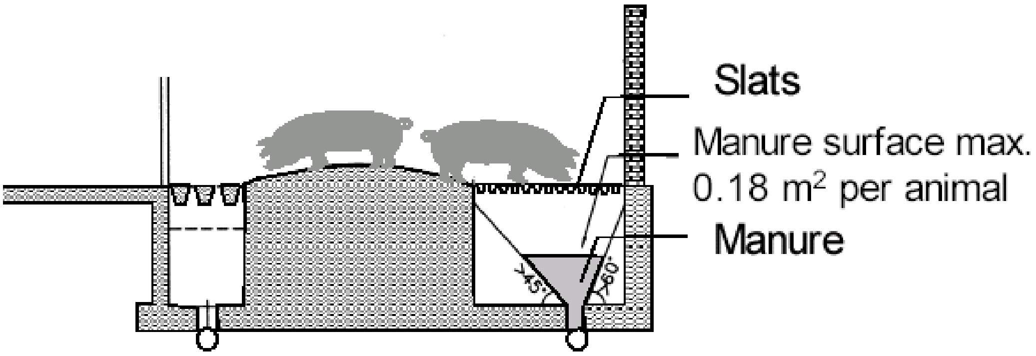


Figure 8: Schematic depiction of the housing system with a reduced emitting surface in the manure pit underneath the slatted floor (Source: Ogink & Aarnink, Wageningen, The Netherlands).

Disadvantages:

With respect to e.g. cow comfort, observations suggest that cows prefer to walk on solid floors and avoid slats if they can. If cows are reluctant to step onto the slats, one has replaced one avoidance problem with another. The aversion to slats is minimal on a good quality waffle slat, so this would be the best choice.

A second disadvantage would be the cost of the pit which would be high if it was there for no other reason and minimal if it was needed anyway for manure handling.

The overall mitigation effect of partly or fully slatted floors depends on the manure removal frequency and the removal system (see 1.2.13).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.2.13 Frequent manure removal

Details of measure:

If excreta are not removed immediately into closed manure stores, NH_3 is emitted from housing systems with exhaust air. These NH_3 emissions from cattle, pig or poultry housing systems can be reduced through regular (weekly, daily or several times per day) washing or scraping the floor. A number of systems have been tested involving the regular removal of the slurry from the floor to a (covered) store outside of the building by either flushing with water, acid or diluted slurry, or scraping with or without water sprinklers.

- Flushing systems (flushing with water (water sprinklers), acid or diluted slurry):

There are many different types of flushing systems. Low-emission flushing systems remove the manure from the pit rapidly.

- Flushing gutters (for pig and cattle housing):

Flushing gutters (45 °) under the slatted floor and the implementation of a pressure conducting wash the slurry out of the stable 1-2 times per day (Figure 9; Meissner & Van den Weghe, 2003) or up to 6 times per day. Flushing is done in open gutters or under slats.

- Vacuum systems

In Figure 10 a conventional fully slatted floor pig housing system with an underlying pit (50 cm deep) employing continuous overflowing and emptying at the end of fattening period (reference technique) is compared with a vacuum system for rapid and frequent slurry emptying (Navarotto et al., 2002).

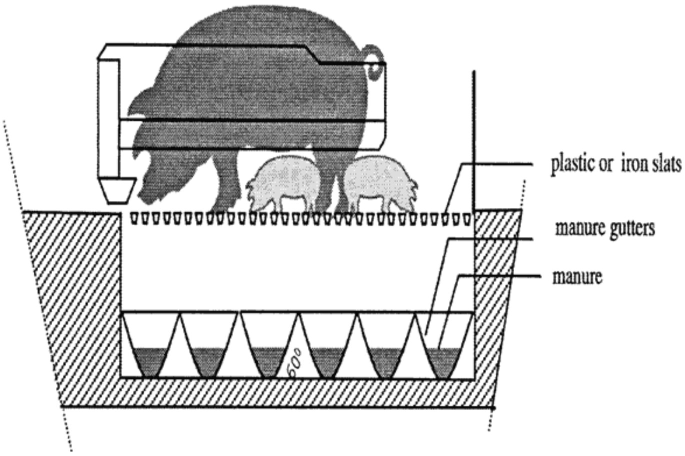


Figure 9: Fully slatted floor with flushing system and manure gutters.

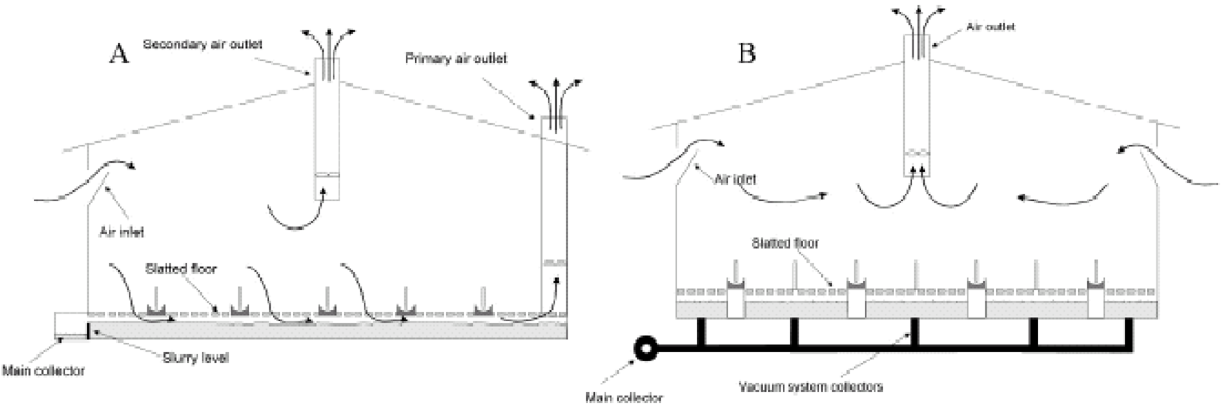


Figure 10: Layout of experimental pig housings. A: reference; B: vacuum system housing (Navarotto et al., 2002).

- Scraping systems

Open channel scrapers as well as under-slat scrapers have both proven reasonably successful and easily adapted to most existing buildings. The open channel scraper is less expensive to install and easier to maintain, but animals can be injured if they are caught between the scraper and pen partitions. Scarping under slats minimises these disadvantages. However, repair and replacement of parts under slats is more difficult and construction costs are higher.

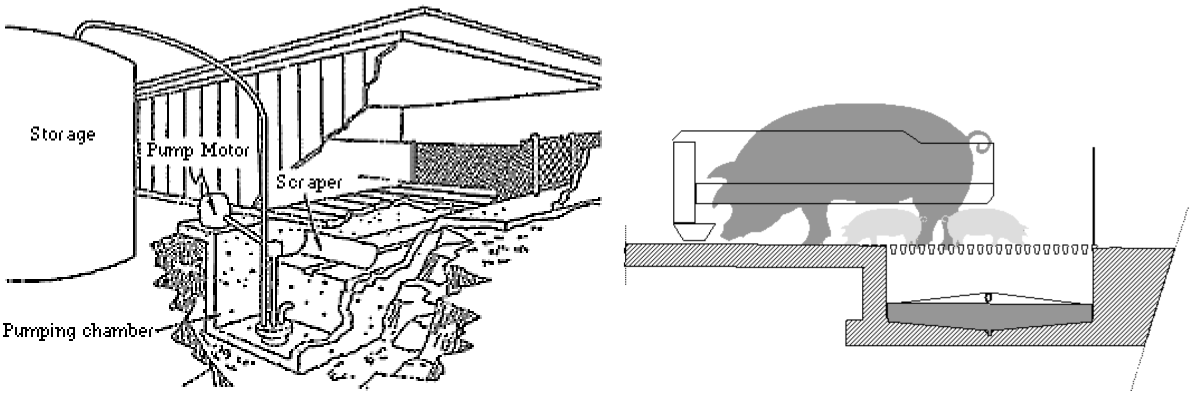


Figure 11: Under-slat scraper system with pumping chamber and above-ground storage (Source: NebGuide).

- Toothed scraper (toothed scraper running over a grooved floor)

One of the most promising systems to date for a frequent removal of manure involves the use of a "toothed" scraper running over a grooved floor. This appears to produce a clean, and therefore lower-emitting floor surface, while still providing enough grip for the cattle to prevent any problems of slipping.

Advantages:

A regular manure removal for livestock housing may directly reduce NH_3 volatilisation and indirectly reduce NH_3 emissions by reducing the urease activity on the slats and solid floors (Voermans & Verdoes, 1994; Voermans et al., 1995a, b; Voermans & Hendriks, 1996; Zeeland & Verdoes, 1998; Zeeland et al., 1999; Verdoes et al., 2001).
Groot Koerkamp & Montsma (1994) showed that decreasing the removal interval from 70 to 40 hours also significantly reduced NH_3 emissions of an aviary system (multi-floor system) (see 1.2.6).

Flushing gutters:

Flushing gutters significantly reduce CH_4 emissions compared to a reference system with fattening pigs (Meissner & van den Weghe, 2003). According to Kiuntke et al. (2001) and Zeeland & Verdoes (1998) NH_3 was reduced.
Flushing systems minimise odours within buildings and are easily adapted to many existing structures. Labour requirements are low.
If acids are used for flushing, emissions will further decrease because of a change in pH. Manure pH can be lowered by adding e.g. nitric acid (see 1.5.3, 2.9.13). Other acids that can be used are hydrochloric acid, sulfuric acid, and phosphoric acid, but nitric acid is the most popular since the other acids affect manure quality. An additional distribution of acid is needed and it will increase the nitrogen content of the slurry.

Vacuum system:

Measurements of Navarotto et al. (2002) show that a vacuum system seems to reduce NH_3 emissions of fattening pigs significantly compared to a reference system.

Scraping system/Toothed scraper:

Scraping systems, especially with toothed scraper, have a significant potential to reduce NH_3 from different animal housing systems.

Disadvantages:

Generally, some of these systems have proved to be ineffective or too difficult to maintain. The use of smooth and/or sloping floors to assist in scraping or flushing has given rise to problems with animal slipping and potentially injuring themselves.

For flushing systems the risk involved with the use of acid must be considered. It is more likely that water will be used but washing the floors with water will not affect CH_4 and N_2O emissions.

Toothed scraper systems give rise to high investment costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↑

1.3 Grassland and grazing management

Pasture and grazing management, which primarily involves beef cattle and sheep, includes improved grasslands and pastures, as well as management of stocking rates and rotation of pastures. Reducing stocking rates and managing distribution reduces the amount of livestock CH_4 produced per hectare, while increasing plant diversification and enhancing carbon sequestration.

By effectively managing grazing, GHG emissions can be influenced. Appropriate stocking rates, seeding with appropriate grass and legume species, improving range condition to the "good-plus" rating and other techniques are being assessed, on a biological-ecological basis.

Cutting and grazing management greatly influences forage quality, productivity, and persistence. Quality is most affected by maturity stage at harvest.

Increasing the quantity of forages used to graze animals is another consideration. A variety of management options, such as rotation and improving native grasslands, all have potential to decrease GHG emissions.

In general, grazed grass is the cheapest feed for dairy cows and sheep, although ruminants are relatively inefficient at converting grass protein into milk protein. But only about 20-25 % of the grass protein is incorporated into the milk with most of the remainder being excreted (faeces and urine). This is not only inefficient but also contributes to environmental pollution.

1.3.1 Extension of grazing in comparison to animal housing

Details of measure:

An increasing number of dairy operators are switching to grazing-based production systems (see 3.3). Research showed that for a typical dairy farm a grazing-based operation produced higher average annual net returns than a confinement system.

Urine excreted during grazing often infiltrates into the soil before substantial NH_3 emissions can occur. Because of the relatively low losses from grazing compared with losses from the housed phase, one suggestion has been to extend the grazing season so that the amount of excreta produced indoors is reduced (Pain & Jarvis, 1999).

Advantages:

Several studies reported that NH_3 emissions per animal are lower for grazing animals than for those in housing where the excreta are collected, stored and applied to land (Pain & Jarvis, 1999).

Additionally, cost advantages of 10-15 % are estimated by Waßmuth (2002). Waßmuth (2002) also appraises that the extension of grazing will result in an increase in animal welfare and health as well as a reduced amount of ectoparasites and respiratory diseases.

A higher share of grazing will also lead to more landscape conservation.

Disadvantages:

Grazing animals contribute to slightly more than 10 % to the global N_2O budget (Oenema et al., 1997). Emissions are partly caused by the fact, that the distribution of N returns via grazing animals are more heterogeneous than if applied as manure, and more exposed to leaching losses because of extremely high point levels. In this regard, patches are important sites for N loss via NH_3 volatilisation (Jarvis et al., 1989), via nitrate leaching (Ryden et al., 1984) and via denitrification and N_2O emissions (Ryden et al., 1986). According to Oenema et al. (1997) grazing animals affect the emission of N_2O in three ways, by 1) return of N in urine patches, 2) return of N in dung patches, and 3) treading and trampling. Also Velthof et al. (1998) argue that grazing-derived emissions are sometimes larger than N fertiliser-derived emissions.

Mosier et al. (1998) reported that N_2O emissions from livestock are much higher when animals are in the meadows than when they are in animal housing systems. Therefore, N_2O emissions from animal waste management can be reduced by restricting grazing (Velthof et al., 1998). This will result in a shift from high N_2O emissions during grazing to lower emissions from anaerobic waste management systems. When grazing is restricted, the cattle will be stalled for a longer time and more urine and dung will be collected and stored as slurry. Here, various technical measures are available to control and reduce emissions (see 1.1, 1.5, 1.6 etc.). The slurry will then be applied as fertiliser to grassland (by the use of improved application techniques, see 2.10) and, consequently, less N fertiliser will be required. Consequently, the N_2O emissions are larger for dung and urine patches in grassland than for slurry which has been properly applied to soil. Therefore, total leaching-derived and N fertiliser-derived N_2O emissions will also be lower when grazing is restricted. Thus, restricted grazing may rather be an option to mitigate N_2O emissions from intensively managed grasslands than an extension of grazing.

But generally, the emission reduction achieved by increasing the proportion of the year spent grazing will depend on the reference system, the time animals are grazed, the fertiliser level of the pasture etc. However, other technical aspects should also be taken into account when considering restricted grazing. This system requires larger slurry storage basins and sophisticated slurry application equipment.

Finally, the potential for increasing grazing is often limited by soil type, topography, farm size and structure (distances), climatic conditions etc.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↘	↗	↗	↘

1.3.2 Adaptation of fertilisation on demand

Details of measure:

To optimise fertilisation management and to minimise environmental impacts due to organic fertilisation it is necessary to evaluate the amount of fertiliser based on the physiological nutrient uptake of grassland or pastures (and crops; see 2.9.3). Therefore, the nutrient supply (N, P, K, Ca, Mg etc.) must be synchronised with the crop demand.

A nutrient budget is the comparison between all sources of nutrients available to the farmer and the requirement of nutrients to meet the plant and soil needs. The sources can either be from on the farm, such as livestock manure, or from off the farm, such as purchased fertiliser. The requirement is the amount of nutrients needed by the grass and pasture plants to obtain the expected yields.

Most values of nutrient availability from different sources and plant nutrient requirements are based on long-term historical averages and grassland/pasture research; i.e. both the nutrient requirements and availability are based on climatic and soil conditions of the past. These values are given with some surety that the plants grown will be supplied with adequate amounts of nutrient during the growing season. All environmental losses, such as run-off and leaching, have been accounted for. Climatic conditions, particularly temperature and soil moisture, greatly influence both the plant performance and the soil's capacity to provide nutrients to the plant. During any growing season the climatic conditions may affect both the plant growth and soil delivery of nutrients to the plant.

Although a nutrient budget is not an exact formula for supplying nutrients, it is one method for organising the nutrient needs of the pasture and grassland areas with the nutrients available on the farm. Nutrient budgets can easily determine if there is a gross imbalance between the nutrients that are available vs. the amount required. Thus, nutrient budgets are one of the best methods to see the overall supply of plant nutrients available compared to the estimated plant needs as given by historic records and field research. Continued use of soil testing (see 2.9.1), plant and manure analyses (see 2.9.2), and yield monitoring are essential to maintain a good nutrient balance with desired results.

Advantages:

By fertilisation on demand, soil nutrient depletion on the one hand and on the other hand nutrient excess, leading to leaching are avoided. This increases the productivity of the whole farm and thus significantly decreases the GHG emission per product unit.

Disadvantages:

Grass-clover pastures may have increasing clover-percentages and therefore N contents during the grazing season could rise. This can result in a negative feedback with higher N intake and N excretion, especially if milk production is decreasing.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↑	↗	↑

1.3.3 Consideration of pasture age and composition

Details of measure:

Animal performance on pasture is directly related to forage quality, i.e. the amount and palatability of the forage, nutrient concentration, and digestibility.

The quality of the forage in any given pasture is a function of three separate but related factors: 1) species composition, 2) their stage of maturity, and 3) the time of year. Generally, the leaves of legumes are higher in quality than the leaves of grasses. Grass leaves are almost always of a higher quality than the stems of either legumes or grasses, and young green leaves and stems are higher in quality than those that are old or dead. As a rule, the younger the plant or plant part, the higher the quality.

As the proportion of lower stem and dead leaf material increases with growing maturity, the share of high quality green leaf material decreases with time. As a result, pasture quality tends to be higher in the spring and autumn as compared with midsummer.

Consequently, the age and composition of pasture can influence the quality of the forage, the productivity of animals and with it the potential to mitigate GHG emissions.

To improve pasture quality, a partial or total pasture renovation may be necessary. Pasture renovation can be defined as a series of actions that lead to a permanent or long-term change in the botanical composition of a pasture. The intended changes are designed to improve the species composition or to increase the population of a selected species in the pasture.

Advantages:

A successful pasture renovation can extend the productive life of a pasture, improve pasture quality, increase pasture carrying capacity, and/or replace old or diseased pasture species with healthy improved varieties.

The pasture quality is influenced by plant species and age, soil fertility, seasons, and drought, among other factors. Better pasture management will ensure higher quality of feed for increased milk production. Hence, GHG emissions are reduced by higher unit area productivity. Young herbages, ensiled forages (grass or maize silage), and legume-based forages all produce lower CH_4 yields than their respective old, dried and grass counterparts (Moss, 1992; Jarvis & Pain, 1994). Thus, also N_2O emissions can be decreased by a higher N efficiency.

Disadvantages:

To ensure success, the renovation of pasture or hay fields must be carefully planned, well ahead of the envisaged planting date. The renovation techniques are expensive and need additional seed and fossil fuel for operation (including additional GHG emissions).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.3.4 High sugar grasses

Details of measure:

Animal production responses are often disappointing on temperate perennial ryegrasses and this is largely related to the poor utilisation of forage protein in the rumen. On fresh forages up to 40 % of dietary nitrogen may be lost as rumen ammonia because the microbial population in the rumen is unable to incorporate much of the non-protein nitrogen released during foliar proteolysis. This may be ameliorated by the addition of sources of readily available energy. This may be possible through the use of grasses with a higher water-soluble carbohydrate (WSC) content. Scientists are now breeding grasses with high WSC contents (or "sugars"). High WSC grasses are varieties which, on the average over the grazing season, have a 5 % higher WSC content than a standard grass (however, at certain times during the growing season, the WSC content of the high sugar grass could be up to twice that of the standard varieties).

Recent advances in conventional plant breeding at the Institute of Grassland and Environmental Research (IGER) have resulted in the development of grasses with increased WSC (Lee et al., 2002). Recent IGER studies show that when grass with high sugar content is fed to dairy cows, the grass protein uptake increases, and cows can eat more grass and produce more milk (on average over 20 % more milk) or sheep increase live weight gain (by on average 12 % to control; see in advantages).

Advantages:

Improved sugar levels in the ryegrass leaf not only improve milk and meat production (Table 2) from grazed grasses but also increase the amount of the nitrogen in the grass that can be used by the animal and less nitrogen is lost. High stem sugar content ensures good silage fermentation and results in silage with high sugar levels and therefore a higher feed value. Studies on feeding dairy cows with high sugar grasses showed that these grasses resulted in reduced N excretion rates to the environment (IGER, 2001). The results suggested that the high sugar grasses reduced the feed N loss to the environment by about 24 %.

Table 2: Sheep production from high sugar grass compared to control (according to IGER).

	Control	High WSC
Animal Production [kg Lwt ha^{-1} day^{-1}]	6.94	8.57
Carrying Capacity	32.4	37.3
WSC [%]	8.3	11.6

Disadvantages:

New high sugar grass varieties for productive performance are still being tested in long-term experiments.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.3.5 Increase of N fixation

Details of measure:

Biological N_2 fixation plays an important role as N input to the grass-clover system (see 2.8). The use of e.g. white clover to replace mineral N fertiliser inputs has been suggested as an option for reducing N_2O emissions in grassland (Jarvis et al., 1996).

Advantages:

Van der Werff et al. (1995) estimated N fixation in grass/clover pastures on mixed, organic farms on sandy soils in the Netherlands by assuming values of:

- 40 kg N fixed per tonne of dry matter for red clover,
- 54 kg N fixed per tonne of dry matter for white clover.

For grazed grass/clover pasture in a grass/arable rotation on a sandy loam in Denmark, Vinther & Jensen (2000) assumed that the quantity of N fixed per tonne of white clover shoot dry weight was:

- 38.6 kg N fixed per tonne of dry matter for first and second year mixtures,
- 45.0 kg N fixed per tonne of dry matter for undersown grass-clover.

Wheeler et al. (1997), in New Zealand, estimated the amount of N fixed as:

- 40 kg N fixed per tonne of dry matter for white clover on a high rainfall site.
- 46 kg N fixed per tonne of dry matter for subterranean clover on a low rainfall site.

The additional nitrogen from N fixation allows reducing the application of mineral fertilisers the associated GHG emissions from production and transport.

Disadvantages:

Currently, no contribution from biological N_2 fixation is included in the national N_2O inventories, partly because of uncertainties in quantifying the N_2 fixation in the grasslands (Mosier et al, 1998). According to the guidelines issued by the Intergovernmental Panel on Climate Change (IPCC), inventories for N_2O emissions from agricultural soils should be based on the assumption that 1.25 % of the added N is emitted as N_2O (IPCC, 1997).

The biological N fixation requires optimal grazing management, since much of this N will pass through animals.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↑

1.3.6 Groundwater level adjustments for grassland (e.g. by drainage)

Details of measure:

Adjusting the groundwater level of grassland by optimisation of irrigation and drainage (prevent large groundwater fluctuations or flooding) can be a promising GHG mitigation option (Velthof et al., 1998). Groundwater levels in soil may fluctuate strongly over the year, because of variations in rainfall, irrigation or drainage. Fluctuating groundwater levels promote N_2O emission, because 1) soil air with high N_2O concentrations may be driven out of the soil due to rising water level, and 2) short periods of drying and wetting of soils promote production and emission of N_2O. Preventing a too shallow groundwater level by good drainage of the soil may be an option to reduce N_2O emissions from mineral soils (Clark et al., 2001).

Advantages:

Preventing large fluctuations in groundwater levels will reduce N_2O emissions from agricultural soils. Augustin & Merbach (1996) and Velthof et al. (1996) found higher N_2O emissions from soil with a deep groundwater level than from soil with a shallow groundwater level. When the groundwater level is near the soil surface for prolonged periods, the soil becomes anaerobic and N_2O production from nitrification and denitrification is then low. Thus, maintaining the groundwater level in peat soils at a shallow level (within 30 cm from the soil surface) coincides with lower emissions of N_2O than in cases with deep (>30 cm) groundwater level.

Furthermore, optimised irrigation and drainage can reduce nitrate leaching.

Disadvantages:

Effects of groundwater level on other factors must also be considered, because shallow groundwater levels lead to sub-optimal sward productivity and promote the emission of CH_4, and deep groundwater levels may cause an undesirable shrinking of the soil and promote the emission of CO_2 through mineralisation of soil organic matter. Saggar et al. (2001) have argued that soil carbon levels in New Zealand pastures have changed little over the last 30-50 years but it is noted from their data that at two locations where the soils have been drained, soil carbon levels have more than halved.

Improved drainage is likely to increase nitrate leaching and thus indirect N_2O emissions. Scholefield et al. (1993) found that nitrate leaching from a clay soil increased 3 fold due to artificial drainage. However, the relative increase in nitrate leaching due to improved drainage depends on both N input and soil texture (Scholefield et al., 1991). Although field data are limited, in his dynamic N model Scholefield et al. (1991) suggested that on average nitrate leaching would significantly increase due to improved drainage. It was assumed here that optimising drainage in poorly and imperfectly drained soils, will reduce the emission factor for excreta and fertiliser for these soils, but will increase nitrate leaching losses.

Costs of this measure are unclear but drainage is too expensive only for GHG mitigation.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↘	→	↘

1.3.7 Conversion of arable land to grasslands

Permanent grasslands give the possibility to increase carbon sequestration. As this measure mainly affects the aspects of carbon sequestration it is discussed in more detail in section 2.11.2 'Land use change' within the chapter 2.11 'Carbon sequestration'.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	↗

1.3.8 Cattle winter management

Details of measure:

N_2O emissions from animal excreta are likely to be highest during the autumn and winter period (de Klein et al., 2001). If dairy and beef cattle were kept on feed-pads during these high-risk periods, the excreta collected and re-utilised as effluent, emissions could be reduced as N_2O emissions for urine and dung patches are higher than for effluent, which has been applied to the soil properly (Oenema et al., 1997; see 1.3.1). Regional distinctions have to be considered.

Advantages:

N_2O emissions and nitrate leaching are substantially reduced (de Klein & Ledgard, 2001).

Disadvantages:

Ammonia volatilisation can be increased from manure storage (de Klein & Ledgard, 2001). Storage capacity has to be increased.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.4 Feeding strategies

Animal digestion and excreted faeces/urine are the main sources of greenhouse gases and potential water pollutants from livestock agriculture. Obviously, practices that improve performance and reduce nutrient wastes will help to reduce GHG emissions. The prime sources of greenhouse gases from livestock are rumen-sourced methane, methane from stored manure, and nitrous oxides and ammonia from manure. The nature and extent of these emissions relate directly or indirectly to animal nutrition.

Methanogens, i.e. bacteria present in the anaerobic environment of the digestive tract of ruminants, generate energy for their growth by using H_2 to reduce CO_2 or produce CH_4, which is then emitted to the atmosphere (Mosier et al., 1998b). Fermentation by microflora in the anaerobic environment of the rumen leads to CH_4 emissions ranging from 2-12 % of gross feed energy intake or 5-20 % of the metabolised energy (Johnson et al., 1993; Gibbs & Leng, 1993). Differences in CH_4 emissions among ruminants are related to different levels of feed intake and extent of digestion, which vary with animal type and age. In general, the fraction of feed converted to CH_4 decreases somewhat as feed intake increases. Additionally, CH_4 emissions decrease as feed quality increases. Methane emissions per unit of digestible energy are generally 2-3 times higher on a low quality diet than on a high quality diet when diet quality refers to available nutrient content/unit of feed dry matter.

Methane emissions from monogastric livestock (animals such as pigs) are lower than from ruminants but also vary with diet quality. Uncertainties in CH_4 from these animals are, however, of little concern because about 95 % of animal CH_4 emissions are from ruminants (Johnson et al., 1993; Clemens & Ahlgrimm, 2001).

Ruminants can utilise two types of nitrogen compounds in their diet: true protein and non-protein nitrogen. The digestion of a particular protein depends to a large extent on its degradability. N-use efficiency is related to the balance of protein types and N-sources fed, and on the balance of N-sources and energy "fed" to rumen bacteria. Furthermore, the amount of N excretion depends closely on the feed intake and therefore also on e.g. the milk yields of the cows (Gruber & Steinwidder, 1996). There exists a linear increase between N excretion and milk yield due the requirements of higher intake of nutrients (Kirchgessner et al., 1993). This results in an asymptotic decrease of the specific N excretion per kg milk because the part for maintenance remains constant (Gruber & Steinwidder, 1996; Kirchgessner et al., 1993).

In general, animals should be fed only with valuable feed at officially determined feeding norms based on the animal's need, such that nutrient supply matches nutrient demand. The total nitrogen loss in a farm declines when animal feeding of both ruminant and monogastric animals is well balanced. Efficient rations for animals have to be made taking into consideration nutritive value of feed. It is desirable that the nutritive value of feed available on a farm would be analysed at least 1-2 times per year in a laboratory (see 1.4.2). Moreover, feeding plans and ration compositions must consider region specific conditions.

Feeding strategies can be used in conjunction with grazing technologies (see 1.3) or in feedlots and barns where animal feed can be readily controlled. Feed type (see e.g. 1.4.3) and treatment (also silage treatment) (see e.g. 1.4.5, 1.4.6), type and age of forage (see 1.3.3), feed composition (see 1.4.7), amount of grain in the diet (see e.g. 1.4.7.3), and addition of oil and molasses (see 0, 1.4.8.1) all affect feed efficiency. Generally, techniques that enhance digestibility reduce methane production by limiting the time food spends passing through the rumen (see e.g. 1.4.8). Some data show that methane emissions are lower when leguminous forage is used instead of grass, and when grass silage is used rather than dried feeds. Processing feed, either mechanically or chemically (see 1.4.5, 1.4.6), also increases digestibility. In addition, there are various different methods that increase rumen efficiency (see 1.4.7.6) and additives that increase the productivity of animals (see 1.4.8).

1.4.1 Optimised plant and animal production

Details of measure:

An optimised plant and animal production makes it possible to grow the feed needed on the farm, shortening the nutrient cycle (see 3.1). An optimised combination of plant and animal production in a region allows the reuse of nutrients in the manure.

Advantages:

Surplus nitrogen can be reduced. Tightening the N cycles may reduce N_2O and NH_3 emissions, and lower nitrate leaching. With optimised plant production the feeding plan can be improved in such a way that methane production and emissions from enteric fermentation can be reduced.

Disadvantages:

In many regions of Europe farms are already specialised in either specific livestock or arable farming. All changes would require a large reorganisation of European agriculture.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.4.2 Analysis of forage and fodder

Details of measure:

Forage and feedstuff analysis and control of ration plans is an important management tool in the development of a proper animal-feeding programme.

Knowledge of the quality of a feed helps to determine where, when and which quantity can be fed. Evaluating feed quality without a laboratory analysis can be extremely misleading. Sensory evaluation of hay and other feeds may include 1) stage of maturity, 2) ratio of legumes to grass, 3) ratio of leaves to stems, 4) colour (bleached or green), 5) odour and 6) presence of weed seeds.

The following aspects have to be investigated:

- intake: fibre levels will affect voluntary consumption,
- digestibility: quantity of nutrients absorbed through the digestive system,
- efficiency: ratio of measurable animal production to nutrients supplied,
- anti-quality factors: components of feed that inhibit the point 1-3 above.

Advantages:

Forages can supply about 90 % of the nutrients consumed by an animal. The quality of forage determines the contribution of the forage to animal performance and therewith the total GHG emissions per animal or product unit (see 1.4.3).

Disadvantages:

Forage and fodder analysis is connected with additional costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.4.3 Improve forage quality

Details of measure:

Livestock feeding systems vary enormously, and this results in large differences in the milk and/or meat output per animal. Globally, methane output per kg of feed is nearly a constant except that animals fed with very high concentrate diets emit less. Because maintenance feed requirements remain approximately constant regardless of production, feed requirements and methane output per unit of product decreases with increasing animal productivity (Mosier et al., 1998). Therefore, forages that increase the amount of milk or meat produced decrease the amount of methane reduced per unit of product (see 1.3.4).

High quality legume/grass forage contains more protein, less fibre and more energy, so it can provide more protein and dry matter to the ration, reducing reliance on purchased protein sources to improve the animal production efficiency.

Improved grass cultivars are claimed to increase live weight gain in lambs without changing the quantity of feed ingested (Westwood & Norriss, 1999). This would imply, at the very least, a reduction in methane production per unit of product. It could also result in less methane per animal if there is a direct effect on rumen fermentation because of particular attributes of these forages. Cultivars of perennial ryegrass containing high levels of water-soluble carbohydrates are also available and these have been found to increase animal performance under some circumstances (see 1.3.4).

Advantages:

A study about the use of high quality forages in Canada showed that CH_4 emissions of grazing steers that had access to high quality pastures declined substantially compared to emissions from matured pastures (Boadi et al., 2000).

For the use of legumes in grazing rotations McCaughey et al. (1999) observed lower CH_4 emissions from alfalfa-grass pasture than pure grass pastures.

When purchased N inputs are minimised, the degree of N introduced into the environment from sources outside the farm will be reduced. In general, providing energy from easily digestible, high-quality forages will maximise dairy cow performance and health.
High quality feeds can also substantially reduce the age of first calving, which significantly increases the lifetime efficiency of dairy cows (Mosier et al., 1998; see 1.5.3).

Disadvantages:

At present the ability of grass cultivars selected for improved forage quality traits to reduce methane emissions per unit of feed intake has not been completely assessed. Alternative forage species are promising but more information is needed both on their efficacy and on their ability to be incorporated into individual grazing systems (Clark et al., 2001).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.4.4 Reduction of feed imports / More feed production on farm scale or local level

Details of measure:

The increasing demand for high quality concentrates in the industrial animal production system results in a world trade in ingredients. To sustain the large animal production in the EU, large amounts of feed such as soybeans are imported from outside the EU. Concentrated ingredients are transported over large distances by truck, rail and/or ship, requiring fossil fuels.
The input and output of nutrients can be balanced when a large share of the fodder is produced on-farm or in the vicinity of the dairy farms which allows recycling of nutrients in the manure. On the one hand, fossil fuel is required as an energy source for drying, milling and mixing of concentrate ingredients, and for pelletting the mixed feed to facilitate feeding, to prevent dust, reduce waste and improve digestion. On the other hand, long-distance transports of feed and/or feed concentrates require energy and therewith cause also additional GHG emissions. But Life Cycle Assessment (LCA) shows that transport costs are insignificant at large scales.
For the reduction of the feed imports (above all protein-rich feed) feed purchases cause higher costs, and animal nutrition on soybean meal basis makes the massive application of e.g. maize as an ideal supplement in the animal nutrition for the cover of the energy demand necessary - but for example maize can not be grown in all European regions.

Advantages:

The reduction of feed imports reduces GHG emissions from processing, transportation etc.
Due to the production and use of the feed in the same area a possible reduction of increase of N in soils around the animal production, reducing the potential for N_2O emission, is given.

Disadvantages:

Consequently, if feed imports are reduced a big part of arable land has to be used for e.g. maize cultivation and the grassland becomes less important. However, f the nutrient balance for maize is problematic on the input side (high level fertilisation intensity) as well as on the output side (erosion, surface run-off, nitrate leaching).
The production of smaller concentrate amounts requires more fossil fuel per product unit compared to industrial production due to additional equipment for drying, milling and mixing (and pelletting) of concentrate ingredients.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	→	↘	→

1.4.5 Mechanical treatment of feed

Details of measure:

The modification of the physical structure of the forages involves the mechanical treatments such as chopping, laceration or defibering and grinding (sometimes together with thermal treatments using steam).

The objective of mechanical treatment is to reduce the size of the blades:

- Chopping (by machines with knives or flails) cuts the blades of e.g. straw into relatively long sections (from 1-10 cm). This is not truly a treatment but more of a technique for improving the presentation of long and somewhat tough forage matter, easing its manipulation and handling by the animal. Chopping is useful, for example, when feeding long maize stalks.
- Lacaration, also called defibering (achieved with a type of flail mill but which has no concave sieve) gives shorter but variable sections due to bursting the stalk along its length. This technique, which increases the absorptive capacity of the forage, is used in developed countries to form a carrier for liquid feed supplements such as molasses and whey.
- Grinding (with a hammer mill) produces forage particles, which are less than a centimetre in length.

The particles resulting from mechanically treated forage are usually agglomerated so as to reduce their volume and ease handling. Agglomeration is achieved in a continuous press that produces condensed fodder in pellets. Agglomeration can also be achieved without any prior grinding, either in a continuous press (designed to make compacted fodder or cobs), or in a ram press (which makes compacted fodder or wafers). This type of treatment reduces the size of the particles even if there is no grinding undertaken.

Advantages:

Mechanically treated forage, which has been condensed, compacted or compressed is normally ingested by ruminants in quantities which are superior to that of untreated forage which is more voluminous. This phenomenon occurs because the rumen is able to physically process and rid itself of the reduced size forage particles more quickly, hence physically regulating the ruminants' appetite.

Research has shown that thermal or mechanical treatment, such as grinding/pelletting of hay/dried grass, therefore reduces methane production (Wittenberg & Boadi, 2001).

For conserved silages, there is an opportunity to manipulate particle size, but research is needed to indicate if there is an effect.

Disadvantages:

There are some negative effects of the condensed, compacted or compressed forage, as this accelerated passage through the digestive system allows insufficient time for action by the microorganisms and may cause a reduction to the digestibility.

Although these industrial type treatments are interesting, they are generally costly in energy consumption, which may compensate for the advantages. They are now less frequently used, particularly since the development of more efficient chemical treatments.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	→

1.4.6 Chemical treatment of low quality feedstuffs

Details of measure:

Chemical treatment of low quality feedstuffs (such as fibrous crop residues) allows increasing digestibility and, indirectly, decreasing the share of feed energy converted into methane through enteric fermentation.

These treatments call upon one or other of the following chemical agents:

- oxidising agents (peroxyacetic acid, acidified sodium chloride, ozone, etc.) which decompose the lignin fairly efficiently,
- strong acids (such as those used in the paper industry),
- alkali based agents (lime, potassium, caustic soda either alone or in association and, more recently, ammonia), which are able to hydrolyse the chemical bonds formed between the indigestible lignin and the parietal polysaccharides (cellulose, hemicellulose) which respectively, are completely digestible or partially digestible.

It is clear that no toxic residues should be left by these substances neither for the ruminants consuming the treated forages nor for the microbes residing in the rumen.

The combined effect of these reactions is to cause a significant reduction in the rigidity of the cell structures and a swelling of the cell walls, thereby allowing their penetration by the electrolytes and cellulolytic enzymes from the rumen microbes. These microbes can thus colonise the organic matter more rapidly, decomposing it more quickly and intensively because hydrolysis has already taken place.

Advantages:

Treatments with e.g. sodium hydroxide and ammonium hydroxide have been found to be cost effective methods for reducing methane emissions from enteric fermentation. Alkali treatment reduces the ratio acetate/propionate, resulting in decreased methane emissions.

Disadvantages:

Possibly low overall reduction potential for methane, since, for instance, cows in general already are fed rations with relatively high average digestibility.

Some oxidising agents are prohibitively expensive and have not been used in practice.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	→

1.4.7 Optimisation of livestock feeding / Adjusting livestock feed composition

1.4.7.1 Low nitrogen feed

Details of measure:

Adjusting feed composition to decrease the amount of nitrogen excreted could be one of the most sustainable methods of reducing not only ammonia but also other forms of agricultural nitrogen emissions to water and air.

On average only about one third of feed N is transformed into the protein of animal products, while the rest is excreted in urine and faeces (Kirchgessner et al., 1994). About one fourth of this N may be emitted as ammonia directly after excretion from the animal and during manure storage. The problem is that the extent to which ammonia emissions can be reduced through feeding strategies will be crucially dependent on current feeding practices (reference). The reference varies greatly across Europe and is in many cases not documented.

Low nitrogen feed assumes changes in the composition of the feed such that the nitrogen content decreases. A lower nitrogen content of fodder will reduce nitrogen excretion by animals and consequently NH_3 or N_2O emissions. This can be achieved by 1) the reduction in the level of nitrogen applied to grassland or substitution of grass by silage (cattle), 2) a better tuning of compound feed to the nutrient needs of the animals (especially for pigs and poultry), 3) changes in the composition of the raw materials (especially for pigs and poultry), 4) supplementing diets with e.g. synthetic amino acids (especially for pigs and poultry) (see 1.4.7.2), and 5) replacement of grass and grass silage by maize (cattle) (Klaassen, 1991; Wijnands & Amadei, 1991).

Advantages:

N_2O and NH_3 emissions are largely dependent on the amount of nitrogen excreted by animals. Since a lower nitrogen content of the fodder reduces the nitrogen excretion per animal, NH_3 and N_2O emissions from livestock will decrease accordingly (assuming a constant livestock population) (Velthof et al., 1998).

Disadvantages:

A possible lower milk production can give an increased CH_4 emission from rumen per litre of milk produced.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	→

1.4.7.2 Minimising protein over-consumption / Increase of amino acids

Details of measure:

A reason for high N-losses can be the low quality of the feed protein due to limitations in the contents of essential amino acids. The metabolism requires specific quantities of each essential and non-essential amino acid in order to synthesise body proteins correctly. While non-essential amino acids may be largely replaced by each other, essential amino acids have to be supplied externally and in a sufficient quantity. These metabolic requirements are used in animal nutrition to construct a hypothetic "ideal dietary protein", which contains essential and non-essential amino acids in an ideal proportion (Roth & Kirchgessner, 1993). If this ideal protein were fed at quantities exactly meeting the requirements, the efficiency of N transformation from the feed into the animal product would be maximal and losses via the excrements would be at minimum levels (Lenis, 1989). Real dietary proteins, however, are often quite different from an ideal protein, especially with respect to essential amino acids. This applies especially to protein sources of plant origin, in which the amino acid pattern is limited mainly in lysine, threonine and methionine (Canh et al., 1998). In diets based e.g. on cereals and soybean, the limiting content of these essential amino acids may inhibit the metabolic use of about 30-40 % of the total protein. Consequently, the animals have to consume about 30-40 % more dietary protein to meet their metabolic requirement compared to a protein with an ideal amino acid content. This generates an enormous surplus of non-limiting amino acids (essential and non-essential), whose nitrogen has to be transformed into urea and eliminated via the urine.
According to the serve effect of limiting essential amino acids on N excretion, any strategy to raise the protein quality will have a strong potential to minimise nitrogen emissions without affecting the production performance of the animals. Considerable improvements may be achieved already by combining dietary protein sources with complementary amino acids (e.g. dietary inclusions of protein of animal origin). The most efficient way is to supplement the most limiting essential amino acids in a pure chemical form.

For rations composed mainly of concentrates (especially for pigs and poultry), the crude protein content can be reduced if some essential amino acids are added in pure form (mainly lysine, methionine and threonine) to give an ideal protein diet.

For cattle fed mainly on roughage (grass, hay, silage etc.), a certain protein surplus is often inevitable (mainly during summer) due to an imbalance between energy and protein in young grass (see 1.4.7.3). This surplus might be reduced by adding components with lower protein content to the ration (e.g. maize or hay) or by increasing the proportion of concentrate in the ration. The latter option will be limited in grassland regions where roughage is the only feed available.

Advantages:

Farmers usually aim at adjusting the protein content and quality of the ration as closely as possible to individual animal needs. This can reduce the nitrogen excreted in faeces and urine.

According to Canh et al. (1998), a ration with crude protein content of 12.5 % (compared to 16.5 %) reduces the total N excretion of pigs by 36 % and the ammonium/ammonia fraction by 43 %.

Elwinger & Svenson (1996) showed that the reduction of the protein content in the ration of chicken (22 / 20 / 18 %) reduces the N content of excretion (53.2 / 46.0 / 38.9 g N kg DM^{-1}) and subsequently the N losses (22.7 / 17.3 / 15.4 %).

According to Hobbs et al. (1996) efforts to reduce dietary nitrogen and providing essential amino acids in an ideal protein ratio can also reduce odours produced in slurry.

Measures to minimise protein over-consumption can be very cost-effective.

Disadvantages:

A major reason for a poor efficiency is the imbalance in the relative amounts of energy and protein in grass. Proteins in grass are broken down rapidly when they enter the cow's rumen, and microorganisms use the products of breakdown (amino acids) to grow and produce more protein that is later digested in the small intestine and used by the cow to produce milk. However, when the diet lacks readily available energy such as sugars, rumen microbes either cannot grow or, use the amino acids to provide energy instead. This means less of them can be used to produce protein. To use amino acids in this way is a wasteful process, which results in much of the nitrogen being released from grass into the rumen as ammonia. This ammonia is then absorbed by the animal and is eventually excreted in urine.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.4.7.3 Replacing roughage by concentrates

Details of measure:

Microbial digestion of fibres from roughages (cellulose) and starch (from grains) results in the production of energy for the animal. Rumen microbe species are specialised in their ability to break down either starch or cellulose (monogastric animals, such as pigs, are not able to digest cellulose efficiently). When the diet is high in roughages, the fibre-digesting microbes multiply and dominate. In a high-grain diet, the number of starch-digesting microbes increases. Changes in the composition of a ration should be made gradually to allow time for the rumen microbe population to adapt. Any practices that speed up the rate of passage of roughage through the digestive system will reduce the rate of enteric fermentation.

A high proportion of concentrates (grain based feeds) in the diet tends to reduce the protozoa population in the rumen, reduce rumen pH, alter the acetate : propionate ratio and decrease the amount of methane produced per unit of feed intake.

The feasibility to replace roughage by concentrates is greatest in countries where beef and dairy production currently involves high levels of forage (grazed or conserved) such as Ireland, UK and possibly France. There is little potential in countries where beef and dairy production is already intensive (COM, 2000).

Advantages:

Replacement of roughage, which contains a high proportion of structural carbohydrate (fibres), with concentrates, can improve propionate generation in the rumen and decrease emissions of methane (Gerbens, 1998).

Disadvantages:

The proportion of concentrates in the diet needed to cause this effect may well be over 50 %. Some negative environmental side-effects are possible from the intensification of beef production in these regions; also there are some risks to animal health (e.g. acidosis, laminitis).

It should be noted that production of industrial concentrates is an energy-intensive process (with associated CO_2 emissions) and that the production of high quality feed could lead to increased emissions of CO_2 and N_2O from increased fertiliser production and application.

Unlikely in practice for countries with low concentrate and high forage/roughage diets because from economic point of view of farmers operating these systems.

Finally, it should be noted that improvements in the efficiency of conversion of feed into animal product will reduce the amount of methane emitted per unit of product but will not necessarily reduce the amount of methane produced in total. A reduction in the total will only occur if the amount of product produced is constant or rises at a slower rate than the rate of decline in methane emitted per unit of product (Clark et al., 2001).

The costs will vary a lot depending on the costs of forages in different regions.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

1.4.7.3.1 Including more non-structural carbohydrates in concentrates

Details of measure:

Increasing the level of non-structural carbohydrate (NSC) or starch in the diet can reduce methane production. This is because the NSC is readily fermented, and leads to a reduced protozoal population and lower rumen pH. Higher NSC levels in rations could be obtained by changing the composition of concentrates to include more starch or sugars and less fibre (Kreuzer et al., 1986).

Advantages:

Research has shown that increasing the level of non-structural carbohydrate (NSC) or starch in the diet can reduce methane production when increasing the level of NSC (Moss, 1994).

Inclusion of more NSC could also decrease nitrogen excretion, which could reduce N_2O emissions in dairy and other cattle production (Gerbens, 1998).

Disadvantages:

Increasing the level of NSC can give rise to an overall lower ruminal fermentation, which may reduce the conversion of feed energy into animal product and this may be detrimental to the animal's health (e.g. acidosis and fertility problems if NSC levels are too high).

This measure is only interesting for countries like Ireland, the UK and the Netherlands where concentrates contain a lot of high fibre by-product type ingredients.

One problem could be to provide the extra NSC: extra cereals would have to be grown.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.4.7.4 High fat diet

Details of measure:

It is known that the addition of fats reduces the amount of feed fermented. The addition of fats to feedlot rations increases the energy density of diets, thereby allowing the incorporation of more forage and less grain into the diets without compromising diet energy density. Replacing 'low fat' with high fat concentrates (of about 7 %) or addition of fats to grain diets (see 1.4.8.1) could therefore reduce methane emissions from dairy cows.

Advantages:

Gerbens (1998) estimated that replacing 'low fat' with high fat concentrates (of about 7 %) could substantially increase emissions from dairy cows in Western Europe.
Methane emissions were also reduced when 4 % canola oil was added to a diet containing 85 % concentrate in a feedlot study (Mathison et al., 1997).

Disadvantages:

Fats cannot be added to diets more than 5-6 % of the ration, as excessive amounts depress fibre digestion. The impact depends on system circumstances and is only feasible during the indoor periods for pasture-based farms.
Fats can have negative side effects on flavour and health. There is a need for more research in this area to quantify the effect of different types of fat/oil.
Fat addition will involve additional costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.4.7.5 (Multi)Phase feeding

Details of measure:

Multiple phase feeding, in which diets can be automatically adjusted by means of a computer controlled feeding system (Henry & Dourmad, 1993), is a good example of how a herd manager can reduce GHG emissions and increase profitability at the same time. Phase feeding is applicable for all livestock and poultry and could be implemented in the short term. The different feed composition for different age or production groups offers a particularly cost-effective means of reducing nitrogen excretion in pigs and poultry. This, like other diet planning tools, reduces GHG emissions (by reducing manure output) by avoiding overfeeding nutrients.
One of the reasons for high N-losses from pig production arises from the fact that the protein demand of the animals is considerably changing in the course of the production cycle (pregnancy/lactation, start/end of fattening), while the protein content of the feed is often kept constant at the level of maximum requirement. Indeed, such a feeding technique appears to be beneficial especially with respect to working management, but it automatically produces a considerable protein surplus along the whole production cycle. The excessive amounts of protein ingested by the animal have to be eliminated by degrading the protein N to urea and

by excretion via the urine. In pig fattening for example, the dietary protein content necessary to meet the animals' requirement decreases steadily in the course of the production cycle. This decline in protein requirement may be matched more accurately e.g. by using several types of feed with different protein content (e.g. 3-phase feeding).

During the growth of the fattening pig the gain of fat is greater than the gain of protein. Therefore, the energy requirements are also greater than those of protein. In the case of feeding the same compositions of the diet during the whole fattening period, there exists a surplus of protein at the end of the fattening period, which cannot be utilised and from which the N is excreted via the urine and faeces. Therefore, the food composition with regard to the protein content should be adapted to the actual demand several times during the fattening period by (multi)phase feeding (Gruber & Steinwidder, 1996; Kaiser et al., 1998). Regarding sows, there exist considerable differences in the requirements of energy and protein between pregnant and lacting sows. Therefore, at least a two-phase feeding should be used, which can reduce N excretion by 12 % (Heinrichs, 1994).

Advantages:

A ration adapted to the life cycle (e.g. phase feeding of swine) reduces excess nutrients and volume of manure. In total, N emissions from pig management may be reduced by phase feeding compared to universal diets (Roth & Kirchgessner, 1993; Windisch, 2001) which substantially reduces GHG per product unit.

Disadvantages:

Additional work is needed for the preparation of the different compositions of the diet.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↑

1.4.7.6 Increasing rumen efficiency:

Growth of rumen microbes can be influenced by chemical, physiological and nutritional components. The major chemical and physiological modifiers of rumen fermentation are rumen pH and turnover rate and both of these are affected by diet and other nutritionally related characteristics such as level of intake, feeding strategies, forage length and quality and forage : concentrate ratios. Although significant advances in the knowledge of effects of various combinations of these factors on microbial growth have been made in recent years, there is still insufficient information available to identify and control the interactions in the rumen that will result in optimum rumen fermentation. Feeding ruminants on diets containing high levels of readily fermented non-structural carbohydrate has been shown to minimise methane production by reducing the protozoal population and lowering rumen pH. However, this can give rise to an overall depressed ruminal fermentation, which may lower the conversion of feed energy into animal product and may be detrimental to the animal's health. Using diets with extreme nutrient compositions is therefore not always considered likely to be a successful or sustainable method to control methane emissions from ruminants.

A number of possible options have been identified which could increase rumen efficiency without threatening animal health:

- Hexose partitioning,
- Propionate precursors,
- Direct fed microbes (acetogens or methane oxidisers),
- Genetic engineering,
- Immunogenic approach,

- Defaunation.

Almost all of these options need more research and development to determine quantitatively and with certainty the reduction that these options might offer.

1.4.7.6.1 Hexose partitioning

Details of measure:

During rumen fermentation, feedstuffs are converted into short-chain volatile fatty acids (VFAs), ammonia, methane, carbon dioxide, cell material and heat. Animal performance is dependent on the balance of these products and the types and activities of microorganisms in the rumen ultimately control this balance. The VFAs are used by the animal as an energy source while the microbes serve as an important source of amino acids for protein synthesis. Ammonia, methane and heat by contrast represent a loss of either nitrogen or energy unavailable to the animal. By varying diet, it may be possible to manipulate the amount of the feed carbohydrate going directly into microbial growth as opposed to fermentation, which should enhance protein utilisation.

Therefore, hexose partitioning is an option to reduce CH_4 emissions by changes in the diet, which can manipulate the amount of the feed carbohydrate going directly into microbial growth as opposed to fermentation (Meeks & Bates, 1999).

Advantages:

Theoretical studies have shown that increasing the quantity of microbial cells leaving the rumen per unit of carbohydrate consumed may have a large effect on the overall methane production (up to a 35 % reduction; Beever, 1993; Meeks & Bates, 1999).

Theoretically this technology should also enhance protein utilisation and hence reduce ammonia emissions.

Moreover, animal productivity increases which reduces the GHG emissions per animal and thus per product unit.

Disadvantages:

Further experimental research is required to investigate, in vitro, carbohydrate sources that provide improved hexose partitioning and to use this information to design diets with enhanced hexose partitioning for testing in vivo to determine the impact on methane emissions.

The cost of implementing this option could be minimal, as the overall effect would be increased productivity, which would offset any additional feed costs associated with the option. However, no reliable cost or performance data are available at present.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→?

1.4.7.6.2 Propionate precursors

Details of measure:

Within the rumen, hydrogen produced by the fermentation process may react to produce either methane or propionate. By increasing the presence of propionate precursors such as the organic acids, malate or fumarate, more of the hydrogen is used to produce propionate, and methane production is reduced (Meeks & Bates, 1999). Propionate precursors can be introduced as a feed additive for all animals receiving concentrates. The propionate precursor, malate, also occurs naturally in grasses, and it is possible that plant breeding techniques could be used to produce forage plants with high enough concentrations of malate.

Advantages:

In-vitro studies conducted by Martin & Streeter (1995) demonstrated that malate does increase propionate production and decrease methane output. The same workers (Martin et al., 1999) also found that direct additions of malate to the diet of finishing steers improved feed conversion efficiency.

It is estimated that if successful, the option could substantially reduce methane emissions of dairy cows (ADAS, 1998, Bates, 2000) and insignificant less of other cattle (Bates, 2000). There could be other benefits to the livestock industry such as improved feed degradation that would be likely to reduce feed costs. Another possible benefit would be a reduced incidence of acidosis in high producing dairy cows, which could lead to considerable cost savings.

As propionate precursors naturally occur in the rumen, they are likely to be more readily acceptable than antibiotic or chemical additives.

Disadvantages:

Considerable research is needed, but if these techniques were successful then this mitigation option could also be used with extensively grazed animals (malate is the organic acid most studied in relation to methane production although fumarate has also been the subject of some limited work).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.4.7.6.3 Directly fed microbes (acetogens, methane oxidisers)

Details of measure:

Certain microbes in the rumen are known to promote reactions that minimise methane production and it may be possible to introduce such microbes directly as feed supplements. Such microbes include acetogens and methane oxidisers.

Acetogens are bacteria that produce acetic acid by the reduction of CO_2 with hydrogen, thus reducing the hydrogen available for reaction to produce methane (Demeyer & de Graeve, 1991). Although this reaction is theoretically possible in the rumen, populations of acetogens in the rumen of adult ruminants are low and the methane producing reaction tends to dominate. Research groups are currently investigating these reactions with the aim of devising practical solutions for the survival of acetogenic bacteria in the rumen and hence the displacement of methanogenic bacteria (see 1.4.7.6.6). They are present in adult ruminants but their populations are low compared to methanogens and methane-producing reactions dominate. Research is under way in Europe to try to increase the populations of acetogenic bacteria at the expense of methanogenic bacteria (ADAS, 1998).

Methane oxidisers could also be introduced as direct-fed microbial preparations. The oxidation reaction would compete with the production of methane, which is a strictly anaerobic process. Methane oxidisers from gut and non-gut sources could be screened for their activity in rumen fluid in vitro and then selected methane oxidisers could be introduced into the rumen on a daily basis in a manner analogous with current feed supplements.

Advantages:

If research is successful on acetogens and methane oxidisers, this approach would reduce methane and increase the efficiency of production since acetic acid is an important energy source for ruminants.

Emissions of ammonia may also be reduced as a result of more efficient carbohydrate fermentation that requires nitrogen.

Disadvantages:

The research is at a very early stage and is not possible to assess how successful this approach is proving to be (methane oxidisers are less promising than acetogens).

The costs associated with isolating, growing and preparing this type of microorganisms are not clear, but some of these costs would inevitably be offset by improved rumen efficiency.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→?

1.4.7.6.4 Genetic engineering/modification

Details of measure:

Improved level of feed intake with improved genetics or altering the fermentation characteristics of rumen microorganisms by genetic modification has been identified as a mechanism whereby ruminant methane emissions could be reduced.

Recombinant deoxyribonucleic acid (DNA) technology could potentially be used to modify the fermentation characteristics of rumen microorganisms (Amstrong & Gilbert, 1985). Examples of application include an enhanced cellulolytic activity in the rumen biomass for forage fed animals to increase their supply of VFAs and amino acids, and a reduction in methanogenesis accompanied by an alternative hydrogen sink through increasing propionate production.

Advantages:

Genetic engineering has, however, the potential to alleviate new limitations that humans have imposed on the rumen (detoxification, resistance to low pH, the digestion of novel feed materials, etc). In addition, genetic engineering offers an option of engineering rumen bacteria to produce a protein better suited to the needs of the lactating dairy cow. Therefore, by means of genetic engineering rumen microorganisms can targeted be modified to improve the intake of cows and sheep. Thus, such an alteration by genetic engineering of rumen microorganisms could result in improved production efficiency, reduced methane production, a change in milk composition in dairy cows, or all three.

Disadvantages:

The effect of the higher intake of these animals is somewhat unsure, and thus there has to be a degree of uncertainty regarding the reduction potential. The higher yielding cows may have negative side effects from their health, welfare and fertility viewpoints and may lead to further intensification of the industry.

There is, in general, a paucity of information on the genetics of rumen bacteria (Teather et al., 1997). Research is at an early stage and has so far concentrated on the use of molecular biology techniques to quantity and characterise rumen microbial populations. Even if genetically altered rumen microbes did become available their acceptance by both producers and consumers is debatable. The approval of any product/organism would have to meet both national and international regulatory standards for genetically modified organisms (GMOs) and products. This method however, may be unacceptable to the most EU member states as there is considerable opposition to the increased release of genetically engineered organisms into the environment.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	→	?

1.4.7.6.5 Immunisation / Immunogenic approach

Details of measure:

A team of researchers at CSIRO Western Australia have made an application for a world wide patent (two patents on a vaccine) for a method of improving the productivity of a ruminant animal by administering to the animal an immunogenic preparation effective to invoke an immune response to at least one rumen protozoan. The removal of one species of protozoan from the rumen will invoke the improvements in productivity associated with defaunation (see 1.4.7.6.6). It is also believed that by modifying the activity of the rumen protozoan, there will be an indirect effect on the activity of methanogens, due to their commensal relationship with rumen protozoa.

Advantages:

According to some studies it will clearly reduce methane production in cattle and sheep and, in addition, increase productivity. If this option develops successfully, it could be applied to the whole ruminant population.

Disadvantages:

This measure is still at the development stage and it not likely to be available for evaluation purposes until 2008 for cattle (e.g. vaccine).

The costs associated with the immunogenic approach could be high initially due to the monopoly associated with the patents. However, if it also delivers improvements in feed conversion efficiency as seem likely, these costs are likely to be offset by reduced feed costs, leading to a relatively cost effective option.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	→?

1.4.7.6.6 Defaunation (alteration of bacterial flora)

Details of measure:

Defaunation equals the elimination of protozoa from the rumen and is applicable for all ruminant animals (Ushida et al., 1997). The elimination of ciliate protozoa from rumen (defaunation) improves the protein to energy ratio in the nutrients absorbed by increasing the amount of bacterial and sometimes dietary amino acids available for absorption at the small intestine. The increased ratio of amino acids to volatile fatty acids in the nutrients absorbed leads to the better performance observed in the defaunated animals (Bird, 1991).

The rate and degree of fibre degradation in the rumen is altered by defaunation, but the direction and extent of its effect depends on the nature of the substrate (animal diet) for microbial growth (Kreuzer & Kirchgessner, 1988), rumen volume and dilution rate (Demeyer, 1988), and concentration of sulphur (Hegarty et al., 1988) and ammonia (Perdok & Lang, 1988) in the rumen fluid.

Advantages:

Defaunation has been shown to reduce the amount of methane produced in the rumen. It does this in a number of ways: lowered fibre digestion, reduced methanogens populations that are symbiotically associated with protozoa, reduced hydrogen production. The reduction in methane output varies with diet and is higher in concentrate-based diets than in forage-based diets (Itabashi et al., 1984; Whitelaw et al., 1984; Kreuzer et al., 1996).

Disadvantages:

Although it is possible experimentally to eliminate protozoa from the rumen, practical methods have yet to be developed by which protozoa can be eliminated.

The long-term effects on animal productivity of defaunation have not been investigated.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	↘?

1.4.8 Increasing animal productivity through the use of additives

There is increasing interest in exploiting natural products as feed additives to solve problems in animal nutrition and livestock production. A wide variety of feed additives have been suggested to reduce ammonia emissions (Kirchgessner et al., 1994). They mostly aim at reducing ammonia content or the pH by chemical or physical processes and/or advance or inhibit microbial processes to influence methane production:

- Oils / Fats
- Probiotics
- Enzymes
- Antibiotics (Ionophores)
- Halogenated compounds
- Steroids
- Growths hormones - Bovine somatotropin (BST)

Although some of these have proven potential (ionophores), most of them are unacceptable (e.g. BST), have unproven a short-term effect, or have other unacceptable side effects. The exception is probably the ionophores. These are currently licensed for use in non-lactating animals only, and even this is under threat. From a methane viewpoint their use with lactating cows should be considered.

At present, there is generally little scientifically validated evidence on positive effects of these additives (Miner, 1995).

1.4.8.1 Oils / Fats

Details of measure:

The use of edible oils in livestock rations has been researched extensively in recent years for a variety of reasons. Recently, there has been renewed interest because of production efficiency, reduced emissions of greenhouse gases, and the potential to produce meat and milk products with enhanced human health components.

Vegetable oils are more dense digestible energy sources that require less fermentation in the rumen for the energy to be released. Edible oils have been more commonly used in dairy rations as a way to increase energy in the ration. They eliminate the negative side-effects and digestive disorders that can be associated with feeding more fermentable carbohydrates that are found in a high grain ration (see 1.4.7.3, 1.4.7.3.1). With oils, producers have the benefit of increasing energy density in the diet without increasing the risk of acidosis.

The application of feeds with high content of medium-chain fatty acids (MCFAs) such as rapeseed, linseed and sunflower oil, coconut oil, palm kernel oil or genetically modified canola oil have the potential to inhibit methanogenesis in domestic ruminants (Dong et al., 1997; Jordan et al., 2005; Machmüller, 2005). Previous research has demonstrated that there is a potential to reduce methane at the stage of formation using appropriate feeding strategies (Van Nevel & Demeyer, 1996). In order to achieve reduced methane emissions without constraining net energy intake, besides the substitution of structural carbohydrates by non-structural ones (Kreuzer et al., 1986) (see 1.4.7.3.1), dietary fats (see 0) currently seem to be the only natural alternatives to synthetic methane inhibitors, antibiotics (see 0) or biotechnological interventions (Moss et al., 2000).

Advantages:

Edible oil additives such as canola, sunflower and coconut oil etc. may result in a reduction of GHG emissions. While the use of edible oils is mainly still at the experimental stage, these additives appear to inhibit methane-producing microorganisms effectively. *In vivo* experiments of Machmüller (2005) show that coconut oil (3 %) and sunflower seed (6 %) diets considerably decreased the energy loss via methane from the lambs. A persistent methane-suppressing effect was apparent over 7 weeks. Supplementing coconut oil at proportions of 3.5 and 7 % suppressed methane production substantially relative to the unsupplemented diet.

An Agriculture and Agri-Food Canada (AAFC) research project found feeding whole sunflower seeds as a supplement clearly reduced GHG (methane) emissions, while another project utilising 4 % supplemental canola oil the reduction of methane emissions was higher.

Disadvantages:

Machmüller (2005) demonstrated that possible interactions of MCFA with the basal diet in the rumen must be considered when developing effective feeding strategies against methane formation in domestic ruminants.

Another aspect to be mentioned is that increasing the dietary MCFA intake of animals will also increase the MCFA content of animal products, i.e. milk and meat (Scheeder et al., 2001). For human beings, saturated fatty acids are considered to be atherogenic factors (Lairon, 1997) because of their hypercholesterolemic effect, and recommended to be replaced with unsaturated fatty acids (Hu et al., 2001). However, the supposed causal relationship between saturated fatty acids and coronary heart disease is still under discussion. Therefore, for both human beings and domestic ruminants the conclusion can be drawn that it will be a matter of dosage and frequency whether or not the consumption of MCFA will have negative or positive effects on metabolism.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

1.4.8.2 Probiotics

Details of measure:

Probiotics are microbial feed additives, containing live cells and a growth medium, that are developed primarily to improve animal productivity by directly influencing rumen fermentation. They are already widely used in the EU and primarily applicable to the dairy sector (Clark et al., 2001).

Advantages:

According to Meeks & Bates (1999) probiotics improve animal productivity and hence reduce emissions of CH_4 and possibly also NH_3 and N_2O emissions. Wallace & Newbold (1993) reviewed data from trials involving dairy cows and growing cattle fed high concentrate diets and calculated that probiotics improved productivity by 7-8 % (Bates, 2000). This would imply a reduction in the amount of methane produced per unit of product (but it seems as if they are likely to have a small impact on total methane emissions (Clark et al., 2001)).

Disadvantages:

Their productivity effect has generally been found to be small, meaning that even if dairy farmers adopted them widely, they would have a limited impact on total methane emissions.

Further research is required to confirm whether there is any additional effect on methane production per se. Even without a direct effect on methane production, there would be a reduction in methane production per unit of production (e.g. per litre of milk).

Since probiotics are feed additives that are fed daily, they would appear to be only suitable for systems where feed supplements are given on a routine basis.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↗	→	→

1.4.8.3 Enzymes

Details of measure:

Recent studies suggest that special enzymes can improve production when added to the diets of livestock or poultry. Enzymes such as phytase, protease/deaminase, amylase, cellulase and hemicellulase (xylanase) are protein molecules that catalyse specific chemical reactions. Enzymes are specific for their substrates similar to a key being specific for a particular lock. Digestive enzymes are essential to animals because complex feeds are not readily absorbed by the digestive tract unless degraded to more simple molecules. Recently, there has been renewed interest in the use of enzymes in ruminant diets because some fibrolytic (cellulases and hemicellulases) enzymes have been shown to be stable when incubated with protease enzymes. Phytase is an enzyme that catalyses the digestion of phosphates contained in feed and therefore helps animals to use bound-up minerals more efficiently.

Advantages:

Several digestive enzymes have been studied for use as additives to enhance animal performance with success in poultry and swine diets (but they have not been traditionally used in diets fed to ruminants). Enzymes improve feed efficiencies to enhance nutrient retention and reduce nutrient excretion (e.g. amylase and B-glucanase in poultry rations), which can reduce GHG emissions.

Disadvantages:

The understanding of how and when enzymes improve animal production is in its infancy. The amount of enzymes applied to feeds does appear to have effects on animal performance but there is no accepted concentration because methods to measure enzyme activity have not been standardised. Interestingly, high levels of enzymes have resulted in lower milk yields than low to moderate levels of enzyme treatment (Lewis et al., 1999; Kung et al., 2000). Over-treatment of feeds with enzymes may result in interactions with components of feeds or blocking binding sites for enzymes or may prevent attachment by rumen microbes but the mechanisms for this finding are unknown.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

1.4.8.4 Antibiotics

Details of measure:

The Commission proposal for a new regulation on feed additives withdraws the authorisations of the four antibiotic feed additives that are still on the EU market. They are monensin sodium (see 1.4.8.4.1), salinomycin sodium, avilamycin, flavophospholipol. These four antibiotic substances are not currently used in medicines for humans thus avoiding that an antibiotic drug used to cure humans is not efficient because the person it is administered to might have developed an anti-microbial resistance. Peptide antibiotics are used for growth stimulation and can also induce a shift in the pattern of rumen fermentation in favour of propionate, thus reducing methane emissions.

Advantages:

Clear methane emission reductions have been observed by Hendricks et al. (1998).

Disadvantages:

The use of anti-microbial drugs has greatly contributed to improvements in animal and human health. However, overuse and misuse of anti-microbial agents have favoured the growth of resistant organisms. This so-called "anti-microbial resistance" may spread to other microbial populations. Infectious diseases that have become resistant to standard anti-microbial treatment present a threat to human and animal health.

There are consumer resistance to the routine use of antibiotics.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.4.8.4.1 Ionophores

Details of measure:

Ionophores, such as monensin, are chemical feed additives (antibiotics; see 0) that modulate the movement of cations such as sodium, potassium and calcium across cell membranes (Pressman, 1976). Monensin is the ionophore most studied in ruminants although others such as lasalocid, salinomycin, nigercin and gramicidin are available.

In ruminants they affect several pathways of fermentation. When added to the diet, ionophores are claimed to affect methane production in two ways. Firstly, they increase feed conversion efficiency by 1) increasing the ratio of acetate to propionate and decreasing energy lost during feed fermentation and 2) decreasing breakdown of feed protein and bacterial protein synthesis, which makes high-roughage feeding more efficient. This increases productivity (weight gain per unit of feed intake) by adjusting several fermentation pathways, which reduces methane output per unit of product. Secondly, because of their effect on rumen fermentation, they directly reduce the amount of methane produced per unit of food intake.

Advantages:

Ionophores, especially monensin inhibit methane formation by rumen bacteria and could significantly reduce emissions if used extensively in the beef, sheep or dairy sector. Monensin added at 24 ppm in a diet of dairy cows clearly decreased CH_4 emissions (Kinsman et al., 1997). Ionophores also decrease the amount of N excreted by ruminants and should therefore help to reduce N_2O emissions from pastures (Clark et al., 2001).

In relation to feed conversion efficiency, a common finding is that ionophores reduce intake but maintain or increase productivity. On high concentrate diets, data from a number of trials indicates that dry matter intake is reduced by 5-6 % whereas feed conversion efficiency increased clearly (Goodrich et al., 1984; Raun, 1990). Thus, animal performance does, on balance, tend to be increased (Parrot et al., 1990; O'Kelly & Spiers, 1992).

An increase in feed conversion efficiency has been observed by Chalupa (1998) and a reduction in methane production by Van Nevel & Demeyer (1992), but the persistence of this reduction is, however, unproven.

Disadvantages:

Ionophores appear to have the greatest potential of the options currently available, although there is considerable uncertainty surrounding both their short and long term efficacy and acceptability (Clark et al., 2001). Experiments show that while ionophores are effective, the bacteria adapt rapidly so that the methane reduction is only temporary (Johnson & Johnson, 1995). Another caveat is that very little of the evidence comes from grazing animals. To reduce methane at a reasonable cost, ionophores also need to increase animal performance.

Ionophores are currently not licensed for use in dairy production in the USA and the European Union because a withdrawal period is required before human consumption. In New Zealand and Australia it is licensed for dairy cows but as an animal health product (e.g. bloat control) and not specifically for use as a means of increasing productivity or decreasing methane production.

However, measurements of CH_4 emissions from grazing ruminants need to be made to confirm the promise as a tool for reducing methane and the long-term effects of ionophores on methane output need to be studied.

There may be consumer resistance to the routine use of ionophores as they are a type of antibiotic (Clark et al., 2001).

The cost benefit analysis for ewes made by Clark et al. (2001) shows that the cost of treatment with monensin is high relative to revenue and a 15 % increase in animal performance is needed to recover the cost of the treatment. This is higher than the average increase in productivity found experimentally.

Compared to sheep, the calculations for cows show that the productivity gains needed to pay for the cost of treatment are modest, ranging from 2.5 % in cows treated for 100 and 200 days to approximately 5 % for those treated for 300 days. These are well within the range of values found experimentally.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↘

1.4.8.5 Halogenated compounds

Details of measure:

Halogenated compounds (such as bromochloromethane, hemi acetyl of chloral and starch) are potentially strong inhibitors of methane production in ruminants. For example, when added to ruminant diets at a rate of 5 g day^{-1}, bromochloromethane has been shown to strongly reduce methane for up to 15 hours after treatment (Johnson et al., 1972). In addition to reducing methane these compounds tend to decrease intake, have little effect on live-weight gain and therefore increase feed conversion efficiency.

Advantages:

Halogenated compounds fed at hourly intervals completely reduced methane production (McCrabb et al., 1997) and when fed twice daily over an eight-week period, it reduced methane output significantly (McCrabb, 2000).

Disadvantages:

No information is presently available as to when this product will be on the market, what it is likely to cost and what the method of administration will be (Clark et al., 2001). A potential problem with halogenated compounds is that microbial populations may adapt such that methane emissions will no longer decrease over the long term (Van Nevel & Demeyer, 1996). They are also unstable compounds that are potentially toxic to ruminants (Lanigan et al., 1978) and humans. Much more work needs to be done before their potential as a mitigation tool can be assessed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	?

1.4.8.6 Hormones

1.4.8.6.1 Steroids

Details of measure:

The use of anabolic steroids such as progesterone and testosterone improves feed efficiency and weight increase (Heyer, 1994).

Advantages:

Steroids can reduce methane production due to a higher animal performance (Heyer, 1994).

Disadvantages:

The acceptance by both producers and consumers is debatable.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↘	↗

1.4.8.6.2 Growth hormones - Bovine somatotropin

Details of measure:

Growth hormones are enhancing agents that can act directly to improve productivity. Bovine somatotropin (BST) is a naturally occurring protein that modifies the nutrient partitioning in lactating dairy cows toward milk production. BST is a protein hormone produced by the pituitary gland, a very small gland located at the base of the brain that affects growth and other physiological processes, such as lactation in dairy cows. The objective in work with somatotropins is to elevate natural levels using genetic engineering techniques (see 1.4.7.6.4) to increase production. The impact of BST is e.g. to significantly increase milk production per cow.

Advantages:

Production responses of 10-15 % during the treatment period (5-12 % over an entire lactation) are expected. Animal stocks could be reduced (Clemens & Ahlgrimm, 2001). A clear reduction of methane release could be achieved in an US dairy herd (IPCC, 1995).

Disadvantages:

Hormone residues can remain in the product, for example in the milk or meat. This practice is currently prohibited in the EU (Heyer, 1994; Clemens & Ahlgrimm, 2001).

Numerous universities and pharmaceutical companies are currently researching its effect on dairy cow production, health and reproduction. Again, this is not a popular consumer choice for enhancing animal productivity and its use is now banned by all EU Member States.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.5 Outdoor manure management (storage techniques)

Livestock manure is handled and stored in a solid, semi-solid or liquid form. Manure form depends on the type of livestock manure and what is added, the amount of dilution water plus the type and volume of bedding used. Liquid manure storages are sources of methane from anaerobic decomposition, and of nitrous oxide due to denitrification from the crust of liquid manure storages. They can also be a large source of NH_3 (60-80 % can, for instance, be lost from pig manure lagoon) as a function of exposure, water content and pH. Covering storage of manure outside prevents the escape of NH_3 during storage (see 1.5.13.4). In addition, losses from slurry and FYM stored outside rise with an increase in temperature (see 1.5.2) and surface area (see 1.5.5), and with the duration of storage (Bussink & Oenema, 1998). Therefore, storage during summer should be minimised because NH_3 losses are much higher in summer than in winter (de Bode, 1991; Sommer, 1992). In addition, the more straw, the higher temperature, the more is the NH_3 loss (Schuchardt, 1990). High moisture content of FYM may reduce NH_3 losses due to reduced gas exchange (Isermann, 1990; Schuchardt, 1990). Manure storage should be of such size that manure would be spread only when the plants can utilise nutrients. The minimum level to be required should be 6 months storage capacity (is dependent on the region, on climate and on crops that are grown). Urine, slurry and FYM stores should be covered or handled by a method that efficiently reduces ammonia emissions and that considers the interdependency between N_2O, CH_4 and CO_2 emissions. If slurry storage is open, at least 15-30 % of nitrogen evaporates during storage. Different biological, mechanical and chemical measures can reduce the formation and/or loss of GHG emissions during storage. In some climates a few options will make manure storage conditions anaerobic, which results in a decrease in N_2O emissions but an increase in CH_4 emissions.

1.5.1 Decreasing or eliminating the airflow across slurry and FYM

Details of measure:

Air speeds across manure-covered surfaces should be minimised since the amount of NH_3 given off by manure is increased with air speed. NH_3 emissions from slurry or FYM stores can be reduced by decreasing or eliminating the airflow across the surface by installing a windbreak (trees etc.) (see 1.2.2.3).

Advantages:

NH_3 emissions are reduced due to the lower airflow over the manure surface.

Disadvantages:

Installation of windbreak could be connected with high costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	↘

1.5.2 Reducing the temperature of manure

Details of measure:

FYM manure or slurry should be stored in a cool (shadowed) and windless site. In addition, the manure may be cooled in the store by water circulated through a pipe system to lower the microbial activity (see 1.2.3).

Advantages:

Cooling of manure to reduce emissions especially NH_3 emissions (microbial activity is lowered). (Groenestein & Huis in't Veld, 1996; den Brok & Verdoes, 1996)

Disadvantages:

Cooling of FYM manure or slurry for reducing emissions would be expensive (equipment for cooling, energy costs for cooling) and would entail additional CO_2 emissions from fossil fuels for electricity needed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	↘

1.5.3 Reducing the pH of manure

Details of measure:

A number of factors influence ammonia volatilisation. One of the most important is pH. Ammonia and ammonium are chemically related to one another and the relative proportions of each are dictated by the pH of the environment. At around pH 9.0, the distribution of ammonia to ammonium is nearly equal but as pH increases, the amount of ammonia sharply increases and becomes the dominant compound. Consequently, acidification of slurry to reduce the pH to lower than 5-6 can reduce NH_3 emissions but also GHG emissions. Such a technique has been investigated with respect to the manure storage (and application see 2.9.13) by Berg et al. (1998) and Clemens & Huschka (2001).

Advantages:

Keeping pH levels at approx. 4.5 will almost completely eliminate CH_4, CO_2 and N_2O losses (Clemens et al., 2002a). Stevens et al. (1989) showed that the treatment of manure with a 5 M sulphuric acid to a pH of 5.5 or 4 reduces the NH_3 emissions significantly.

Disadvantages:

The reduction of pH seems not to be practically possible due to the high cost and/or the technical difficulties.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↘

1.5.4 Manure additives

Details of measure:

Chemical (organic and inorganic acids) and biological (enzymes, microorganisms) additives have been used to abate emissions, but very few independent tests have proven their effectiveness (Frosch & Büscher, 2002). At present approx. 60 compounds are on the market (Mattig, 1991; Kunz, 1995). For pH control sodium hydroxide or lime can be added to manure to raise the pH, inhibiting sulfide production, and preventing release of hydrogen sulfide. Most of these compounds are acidifying agents that reduce the pH of manure (see 1.5.3).

For the biological effects of inhibiting additives see urease and nitrification inhibitors (2.9.7).

Advantages:

Berg (1998) reported that lactic acid reduces methane and nitrous oxide emissions significantly and that the benefits of acidification extend not only to the animal house, but also to manure storage and land application. According to Frosch & Büscher (2002) lactic acid reduces NH_3 but in particular methane emissions. Stevens et al. (1989) showed that the treatment of manure with a 5 M sulphuric acid to a pH of 5.5 or 4 reduces the NH_3 emissions nearly completely. Also Kroodsma et al. (1994) clearly reduced NH_3 emissions of cattle slurry when treated with 12 M nitric acid.

In addition, odours are reduced significantly by the use of different manure additives.

Disadvantages:

The impact is dependent on the composition of the slurry or FYM - some literature references also report neutral or negative results. In general, the effectiveness of additives is often unclear as 1) products are in most cases only a limited time-frame in trade or are only offered on a regional level, 2) the product names change frequently, 3) additives often represent test products and 4) in the majority of cases not all ingredients are listed.

Often high (and thus expensive) amounts of additives are needed to achieve the desired result.

The use of strong acids (such as H_2SO_4 and HNO_3) for agricultural purposes is inappropriate due to high costs and associated dangers (Vandré & Clemens, 1997).

Kunz (1996) reported a considerable variability when testing the effect of 30 slurry additives.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↘

1.5.5 Reducing the surface per unit volume of slurry or FYM stores

Details of measure:

NH_3 and CH_4 emissions (and dependent on the manure surface also N_2O emissions) from slurry or FYM stores can be decreased by reducing the surface per unit volume of the slurry or FYM store (de Bode, 1991; Sommer, 1992; Hüther, 1999). If for example lagoons are replaced by tanks (see 1.5.13.2), NH_3 and CH_4 emissions may be reduced due to the lower surface area per unit volume. In general, about 90 % of manure's methane potential and about 80 % of NH_3-N can be lost to the atmosphere from open lagoons (e.g. under warm conditions in south Europe).

Advantages:

The covering of manure storages can additionally reduce temperature and reduce methane (see 1.5.12.3, 1.5.13.4). N_2O produced in the surface crust may be lower compared to the reduction of the surface area. Covered storages can also reduce additional moisture and added anaerobic conditions.

Disadvantages:

Lagoons are easier to handle.

Changing from lagoons to tanks might be expensive.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

1.5.6 Mechanical separation of solids of manure

Details of measure:

Liquid and solid fraction of slurry can be separated so that their maximum usable potential can be exploited. Currently, both mechanical and gravity methods are used to separate manure (details of methods see 1.2.11). It is recommended that vibrating-screen, stationary sloping screen or pressure-roller mechanical separators should be used so that a relatively dry solid by-product can be recovered. Recovered solids can be used in composts for eventual use as fertiliser, while liquids can be used as an effective and easy to handle fertiliser.

Advantages:

Liquid with low solid content is easier to handle and has a higher fertiliser value and lower NH_3 and N_2O emissions after application.
The mechanical separation may reduce odours.
Solids can be spread on land or used as bedding (after one full year of aging).
The separation can reduce lagoon/tank loading (lagoon/tank size requirement is less).

Disadvantages:

The farmer has to handle both liquid and solid fraction.
Separate storages may cause higher costs.
Storage of solid fraction may increase NH_3 emissions.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

1.5.7 Composting of solid manure or slurry with added solids or of FYM

Details of measure:

Composting is the controlled decomposition of organic material such as manure by aerobic treatment into a more stable organic form and is possible for all solid manures. Aeration involves dissolving sufficient oxygen in the liquid manure to allow bacteria to oxidise the organic carbon (see 1.5.12.5). Therefore, aerobic processes lead to the production of CO_2 instead of methane. Great care must be taken to guarantee that proper composting procedures are applied: composting requires sufficient oxygen supply in the FYM heap. This presupposes an adequate content of straw as well as repeated, thorough turning of the FYM (see 1.5.12.5). Composting is an option for operations that separate solids (see 1.2.11, 1.5.6) and can result in a marketable product.

Advantages:

Composting of solid manure or slurry with added solids can significantly reduce N_2O emissions in comparison to usual manure storage emissions (Amon, 1998). Furthermore, a controlled aerobic decomposition of manure could effectively cut the potential methane emissions of stockpiling (Amon, 1998). The drier the manure, the lower its methane emissions will be. This is due to higher oxygen penetration and aerobic conditions that encourage the production of carbon dioxide instead of methane. Turning compost heaps and

manure piles ('aerated composts') increase oxygen exposure, and this in turn reduces the formation of methane.
The optimised C/N ratios can also reduce NH_3 emission (Jacobson et al, 1999).
The dry-end product can easily be handled, manure volume is reduced, an excellent marketable soil conditioner is produced, risk of pollution and odours, pathogens, weeds and seeds is reduced. Because compost has been stabilised by aerobic decomposition and therefore has no odours it can be used in locations where manure use would be objectionable.

Disadvantages:

According to a few studies improper composting (due to poorly managed composting processes) is likely to increase emissions of NH_3, N_2O and CH_4 and will thus not result in environmental benefits (i.e. aerobic decomposition or composting of animal manures may cause much higher NH_3 emissions (Kirchmann & Lundvall, 1998), but in combination with effective separation of urine from faeces/bedding these N losses could be reduced).
Composting increases time, money, machinery, land and energy requirements and possibly odours during composting. According to Raupp & Baur (2000) the reduction is not cost effective (working hours, turn over of the FYM) at this stage (at least regarding the nutrient contents). Hence, there is considerable uncertainty as to the effectiveness of this treatment.
Systems for aeration involve mechanical methods for passing air through the liquid, usually driven by electric motors and require de-watering of liquid manures or addition of other dry organic materials to increase porosity and penetration of air. When considering methane reduction using this technique, emissions of GHG from electricity use should be deducted from any saving.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	↗	↗

1.5.8 Controlled denitrification processes in slurry

Details of measure:

Pilot plants for the controlled denitrification processes in the slurry show that it might be possible to reduce ammonia emissions by transforming ammonium to nitrogen gas by controlled denitrification (alternating aerobic and anaerobic conditions) (UNECE, 1999).

Advantages:

Ammonia emissions can be reduced.

Disadvantages:

The reactive N is a valuable plant nutrient, with an energy consumption (CO_2 and N_2O cost) for fixation.
The option is connected with high costs.
N_2O emissions may be enhanced.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↘

1.5.9 Controlled aeration during slurry storage

Details of measure:

Manure that is stored in earthen basins, pits or tanks undergoes biological degradation. In these cases, the processes involved are relatively uncontrolled and may take a long time. Technologies such as aeration can help accelerate the natural process and can be, for most of the cases, well controlled. Storage aeration is used to maintain the manure in an aerobic state. When manure has sufficient amounts of oxygen present, very little odour is produced, and a significant amount of nitrogen can be removed from the manure by microorganisms. Where the land base available for spreading is limited, it may be necessary to try to reduce the nitrogen content of the manure before it is spread on the land. In addition, methane production and therewith CH_4 emissions can nearly be eliminated.

During the summer (dependent on the region), liquid manure can be treated aerobically by using mechanical aeration equipment. Mechanical aerators operate by either pumping air bubbles into the manure, or by spraying the manure into the air.

Figure 12: Aerated lagoons treating flushed swine manure.

Advantages:

Controlled aeration reduces methane emissions significantly (Amon et al., 2004).
Complete aerobic treatment eliminates manure odours.

Disadvantages:

Studies of Amon et al. (2004) showed that NH_3 emissions could increase. Moreover, it is in all probability that also N_2O emissions will increase due to manure aeration.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↗	→	↘

1.5.10 Minimising of stirring

Details of measure:

Minimising of stirring of stored cattle slurry of a sufficiently high dry matter content will allow the build-up of a natural crust (see 1.5.13.3). If this crust totally covers the slurry surface and is thick enough (especially for cattle slurry), and the slurry is introduced below the crust (see 1.5.11), such a crust can significantly reduce ammonia emissions at little or no cost. This natural crust formation is an option for farms that do not have to mix and spread slurry frequently.

Advantages:

The emission abatement efficiency - especially of NH_3 - depends on the nature and duration of the crust.

Disadvantages:

Effects on N_2O and CH_4 emissions are unclear and also depend on the composition and texture of the surface crust.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↑	→	↑

1.5.11 Fill-pipe into manure storages underneath the slurry surface

Details of measure:

Filling and emptying liquid manure storage tanks or lagoons from below the surface of the stored manure can reduce GHG emissions by conservation of the slurry surface crust (underslat flushing).

Figure 13: Filling of manure store may degrade the natural surface crust.

Advantages:

With bottom loading of the manure storage a substantial reduction of NH_3 emissions is possible.

Disadvantages:

Effects on N_2O and CH_4 emissions are unclear.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.5.12 FYM storage techniques

1.5.12.1 Increase of straw amounts

Details of measure:

Stored solid manure heaps can be a significant source of nitrous oxide and methane emissions. The manure characteristics influence these emissions and solid manure heaps can be managed to promote aerobic decomposition during storage. Increasing the carbon content of the manure heap with high C additives, such as straw, may provide the opportunity for N_2O and CH_4 emission reduction (Yamulki, 2005). A C/N ratio of at least 25 is recommended, which can be reached by the addition of straw.

Advantages:

Clemens et al. (2002b) reported that an application of straw with a DM content of 22 % results in lab studies in a reduction of N_2O and CH_4 emissions. Also Yamulki (2005) measured a considerable reduction of N_2O and CH_4 emissions after the addition of straw in FYM heaps.

Figure 14: Measurement of N_2O and CH_4 emissions during storage of cattle manure.

Disadvantages:

Straw addition may change the redox status of the FYM. For example the FYM with straw addition may be colonised by aerobic microorganisms that use ambient air as oxygen source for nitrification of the slurry borne ammonia. Also the addition of straw may result in higher CH_4 emissions due to the input of additional carbon into the system (Hüther, 1999) (see 1.5.13.4.1.1).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.5.12.2 Compaction of FYM

Details of measure:

In order to reduce NH_3 emissions from stored manure, it has been recommended to reduce the convection of air into and through the heap. The convection may be reduced through compaction of the litter. The compaction of farmyard manure influences the microbial activity by the creation of anaerobic conditions.

Advantages:

Anaerobic conditions may reduce NH_3 losses (Amon et al., 1999).

Disadvantages:

A negative side effect of this practice for reduction of NH_3 emissions could be an increased production of CH_4 as a result of more anaerobic conditions in the heap (Sommer & Møller, 2000; Jungbluth et al., 2001).
Compaction represents an additional manure treatment that is connected with personnel costs and additional use of fossil fuel and thus higher GHG emissions.
N_2O emissions are likely to be enhanced (Sommer, 2001).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

1.5.12.3 Flexible cover

Details of measure:

Manure heaps can be covered by flexible cover to reduce the convection of air into and through the heap.

Advantages:

The coverage of manure heaps may reduce CH_4 emissions (Sommer, 2001).

Disadvantages:

An increase of N_2O emissions is possible when manure heaps are covered (Sommer, 2001). Also the NH_3 may increase if the coverage increases the temperature of the manure heap.
In addition, to cover the manure heaps complicates the daily addition of FYM.
At present the effect is not definitively clarified (Clemens et al., 2002b).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	↗

1.5.12.4 Comminution of FYM

Details of measure:

The repeated comminution of manure heaps with a discharge spreader represents a technical measure to influence the microbial conditions in FYM.

Advantages:

Measurements of Sommer (2001) showed that the repeated comminution of FYM significantly reduces the total GHG emissions compared to a reference FYM storage. The reduction of the CO_2-equivalents is mainly caused by the decreased N_2O emissions.

Disadvantages:

The comminution of FYM is time-consuming, needs additional fossil fuels (including GHG emissions) and therefore is a costly mitigation measure.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↘	→	→

1.5.12.5 Repeated turnover of FYM

Details of measure:

A repeated turnover of FYM represents an equivalent to composting (see 1.5.7).

Advantages:

According to Clemens et al. (2002b) N_2O and CH_4 emissions are significantly reduced due to a repeated turnover of FYM if throughout and careful turnover is carried out.

Disadvantages:

The comminution of FYM is time-consuming, needs additional fossil fuels (including GHG emissions) and therefore is a costly mitigation measure.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	↗	↗

1.5.13 Slurry storage techniques

1.5.13.1 Consideration of the filling level

Details of measure:

The consideration of the filling level is important for an optimal (reduced) airflow above manure surface, manure temperature etc. (see 1.2.2.2, 1.2.8).

Advantages:

An optimised (reduced) filling level can especially reduce NH_3 emissions due to the lower airflow over the manure surface.

Disadvantages:

Sufficient or additional storage capacity is needed if the filling level must be lowered.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

1.5.13.2 Tanks instead of lagoons

Details of measure:

If tanks replace lagoons, emissions may be reduced due to the lower surface area per unit volume (see 1.5.5).

Advantages:

Results of recent studies show that the NH_3 emissions of pig slurry storage are higher compared to cattle slurry. This is caused by the higher NH_4^+ content of pig slurry and by the surface crust of cattle slurry that reduces the NH_3 emissions. Thus, the mitigating effect would be higher for pig slurry than for cattle slurry.
Moreover, smaller volumes of slurry would be generated, largely by the exclusion of rain water from stores. Tanks need less area.

Disadvantages:

The potential decrease in N_2O emissions are less certain due to the number of competing effects that need to be considered.

Investment costs of tanks are typically higher than of lagoons.
No reduction of CH_4 emissions is to be due.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	↗	↗

1.5.13.3 Natural crust

Details of measure:

The formation of natural crust serves as a biological cover that can reduce NH_3 and CH_4 emissions (see 1.5.10).

Advantages:

De Bode (1990) reported a clear reduction of NH_3 emissions with a natural crust. Koch (1998) measured a similar NH_3 reduction potential compared to reference. Also Döhler et al. (2002) reported a NH_3 reduction by a natural crust for pig slurry and a significant higher abatement potential for cattle slurry with a high range depending on the development of the surface crust.
Also CH_4 emissions can be decreased.
Studies have shown that a natural crust reduces additionally odour emissions from dairy storages by 75 %.

Disadvantages:

Natural crusts partly may cause substantial increase of the N_2O emissions (Sommer & Petersen, 2002).
The texture of the surface crust depends on the feeding. An increasing share of maize in the ration reduces the development of a surface crust (Berg et al., 2002).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↑	→	↑

1.5.13.4 Cover techniques

The best-proven and most practicable technique to reduce NH_3 emissions from stored slurry is to cover the slurry tanks or silos with low technology covering (straw, peat, bark, granulates or floating oil), a solid lid, roof or tent structure.
While it is important to guarantee that covers are well sealed to minimise air exchange, there will always need to be some small openings or a facility for venting to prevent the accumulation of inflammable gases, such as methane.

1.5.13.4.1 Low technology covering

Aside from rigid covers, plastic foils and roofs, there is a range of flexible or floating covers that can also reduce in particular ammonia emissions but also CH_4 emissions from stored slurries by preventing contact between the slurry and the air.
Generally, the effectiveness and practicality of some of these covers are not well tested and are likely to vary according to management and other factors.

1.5.13.4.1.1 Straw, peat and bark

Details of measure:

For dairy manure at least 4 kg straw m^{-2} and for the more liquid pork manure at least 7 kg straw m^{-2} (15-25 cm) is recommended. Also peat and bark can be used. The straw, peat and bark material can be applied to manure storage tanks using a straw chopping/blowing machine. Which kind of straw is used is not so important.

Advantages:

A substantial reduction of NH_3 emissions is confirmed in lab and in practice experiments (Roß et al., 1998; Wanka et al., 1998). De Bode (1990) significantly reduced the NH_3 emissions by the addition of 4-7.5 kg straw m^{-2}. Also Döhler et al. (2002) reported a clear NH_3 reduction by straw addition for pig and cattle slurry.
Wanka & Hörnig (1997) and Wanka et al. (1998) also reported a reduction of CH_4 and N_2O emission for practice slurry tanks.
An elimination of odours by approx. 70-87 % is estimated by KTBL.
The coverage with straw represents a cheap cover option.

Disadvantages:

Straw covers may change the redox status of the slurry surface. A straw cover may be colonised by aerobic microorganisms that use ambient air as oxygen source for nitrification of the slurry borne ammonia. In lab experiments, there is partly a substantial increase of the N_2O and CH_4 emissions possible (Hüther & Schuchardt, 1998; Roß et al., 1998). The addition of straw may result in higher CH_4 emissions due to the input of additional carbon into the system (Hüther, 1999).
Straw, peat and bark may sink into the slurry after rainfall.
Enough straw material must be available.
Higher straw amounts influence the pump efficiency.
The manure application is more difficult and NH_3 emissions can be higher after application.
Straw is to be used only once.
Peat is not a renewable substrate; a long formation time is needed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.5.13.4.1.2 Granulates

Details of measure:

Granulates like LECA (light expanded clay aggregates) or macrolite balls or other floating material (e.g. perlite) can be used as cover material (Sommer & Hutchings, 1995).

Advantages:

In comparison to straw NH_3 mitigation results are higher with the use of granulates (de Bode, 1990; Miner & Suh, 1997; Hörnig et al., 1998; Hüther & Schuchardt, 1998; Koch, 1998; Döhler et al., 2002).

Disadvantages:

LECA pebbles are not suitable as a cover on thick slurry since the pebbles have limited ability to re-establish as a cover after mixing the slurry.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.5.13.4.1.3 Floating oil

Details of measure:

A layer of floating oil (e.g. rape seed oil of 0.5 cm) on the surface can be used to cover stored slurry (Blanck, 1918; Sommer, 1992).

Advantages:

There is little expert knowledge about the GHG mitigation efficiency of oil floating.

Disadvantages:

A considerable increase in CH_4 emissions is anticipated.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

1.5.13.4.2 Flexible plastic cover

Details of measure:

Flexible covers such as plastic sheeting (e.g. swimming vinyl covering) placed on the surface are mainly used for slurry tanks (but also applicable for manure heaps; see 1.5.12.3).

Advantages:

In general, NH_3 emissions are clearly reduced by the use of plastic covers (UNECE, 1999) Döhler et al. (2002) reported a significantly higher NH_3 reduction potential by a plastic sheeting for a pig and cattle slurry. According to Jacobson et al. (1999) impermeable floating plastic covers nearly eliminate emissions.

Disadvantages:

Due to high costs plastic covers are not applicable for lagoons.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

1.5.13.4.3 Rigid covers and roofs

Details of measure:

Rigid covers and lightweight roofs are permanent covers that are commonly made of concrete, wood, and plastic and used on small and medium sized pits and settling basins. Lightweight roofs can be made of fiberglass, aluminum, and also of thicker flexible plastic membranes (see 1.5.13.4.2).

Advantages:

A significant NH_3 reduction is reported by UNECE (1999), Klimont (2001) and Döhler et al. (2002) by a rigid cover for pig and cattle slurry.

Apart from a significant reduction of NH_3 emissions, rigid covers reduce manure storage volumes (less capacity without rain water - depending on average rainfall) and application amounts by the exclusion of rain water from the stores.

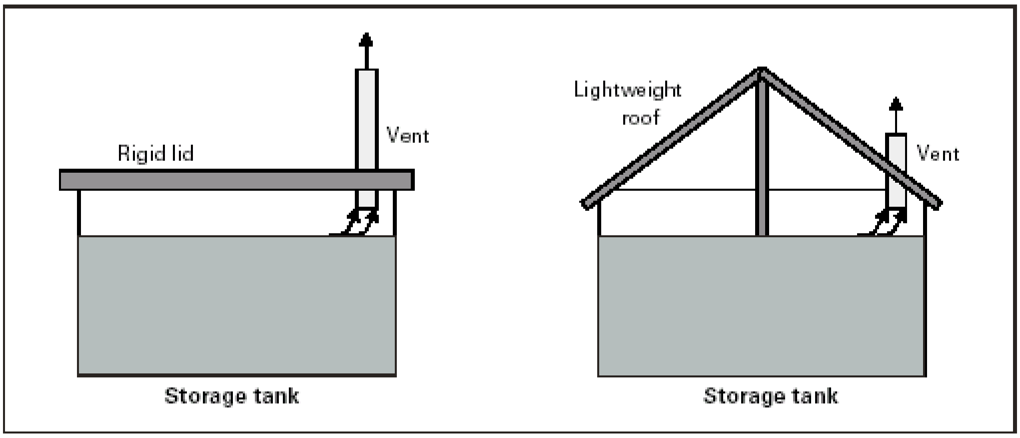


Figure 15: Rigid lid and lightweight roof for manure storage tanks (Source: MidWest Plan Service, USA).

Disadvantages:

Less diluted slurry (dependent on average rainfall) would have a higher nutrient value per application potentially increasing losses of ammonia, nitrous oxide and nitrate leaching at a later date (after application). Thus, an adequate manure application method is needed.

Rigid covers are usually more expensive than other types of covers, but they may last longer (10-15 years, depending on the material).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	↗	↗

1.6 Anaerobic digestion

Details of measure:

Anaerobic digestion is the bacterial fermentation of organic material under controlled conditions in a closed vessel. The process produces biogas which typically consists of up to 65 % methane and 35 % CO_2. The rate of biogas generation is dependent on the rate of anaerobic digestion. Environmental factors affecting the rate of anaerobic digestion include temperature, pH, carbon to nitrogen and water to solid ratios, nutrient composition particle size, retention time and quality of manure and/or co-digestible material agitation.

Methane emissions from anaerobic digestion can be recovered and used as energy by adapting manure management and treatment practices to facilitate methane collection. Anaerobic digestion plants can be small scale, located on a farm, or large centralised plants can be used (Meeks & Bates, 1999). In the case of the latter, other organic wastes may also be taken in to ensure a consistent supply of waste all year round. This can have the additional advantage of higher methane yields from such wastes compared to manure. Both farm-scale and centralised plants can be used to produce heat and/or electricity, which farm owners may utilise, or in the case of centralised plants may be sold (Weiske et al., 2005). Then plants also produce a digestate, which potentially can also be sold as a soil conditioner. Bates & Meeks (1999) have found that income received from digestate can have a significant influence on the cost-effectiveness of the option. Therefore, methane capture and use as energy have a 'double' effect in that the energy produced can offset CO_2 emissions from fossil fuel. The emission of

CH_4 from stored anaerobically digested slurry and cattle slurry has been shown to vary between <0.001 and 1.4 g C m^{-3} h^{-1} (Hansen et al., 2002).
Biogas production is typically carried out in wet fermentation processes (substrates are suspended so that they can pass a pump) but dry fermentation plants are getting more popular but are still on prototype level.

Advantages:

It is assumed that a substantial reduction of CH_4 emissions is achievable in emissions for both farm scale and centralised plants in cool climates, for manures that would otherwise be stored as liquid slurry, and hence have relatively high methane emissions. For warmer climates, where the methane emissions from such manure storage systems are estimated to be more than three times higher (IPCC, 1997), a higher reduction potential is assumed (see 1.6.3.2).
Digestion also prevents N_2O and NH_3 emissions into the atmosphere if an appropriate application technique is used and reduces compounds which are responsible for malodour. The pathogen load can be reduced by up to 99 % and weed seeds are destroyed.
In addition, anaerobic digestion produces an organic fertiliser with a higher value than raw liquid manure. Moreover, biogas production can result in a new income for farmers or produce energy for farm activities.
In general, anaerobic digesters have been shown to:

- improve handling and solids separating characteristics of manure,
- maintain the manure's fertiliser value,
- stabilise manure by converting up to 70 % of organic N into NH_4-N,
- destroy about 60 to 75 % of the volatile solids,
- conserve water and produce marketable digester "fibre",
- reduce BOD levels by up to 90 % and COD by 60-70 %,
- reduce transportation costs by reducing manure solids by 70 to 95 %,
- reduce odour and GHG emissions,
- destroy weed seeds and reduce pathogens by up to 99 %,
- reduce attractiveness of the manure to rodents and flies,
- reduce odour from land-applied slurry by 75 %,
- enable the sale of heat or electricity and provide an energy source to the farm.

Disadvantages:

In practice most digestion plants did not intersperse themselves on the market, because the specific costs reach 13-51 € m^{-3} respectively more than 153-614 € per 500 kg LW and year.
In practice the main constraint on the application of anaerobic digestion to date has been economics. In different European countries plants have received support in the form of capital grants, low costs loans and tax incentives. For example in Germany, Austria and Italy have also secured a niche market for 'green' energy that attracts a cost premium.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	↗	↗

1.6.1 Storage of digested slurry

Details of measure:

Methane and NH_3 dominate the GHG emissions during manure storage. Factors influencing the emissions are the physical and chemical properties of the slurry such as the content of easily degradable carbon, NH_4^+ content, pH, redox conditions, but also dry matter content and viscosity. Emissions are further affected by environmental conditions e.g. wind speed, temperature and the degree of slurry exposure to the atmosphere.

Ammonia and CH_4 emissions originate from the slurry itself. Ammonia is emitted due to the pH controlled equilibrium of NH_4^+ and NH_3. Methane is formed by methanogenic bacteria in the slurry during storage. In contrast, N_2O is formed when the slurry surface dries up during storage.

However, during the process of fermentation, substrate parameters such as DM, ODM and the NH_3/NH_4^+ ratio undergo changes that may affect the potential to emit GHG (Table 3; Clemens et al., 2004).

Table 3: Properties of digested and undigested cattle manure and mixtures of cattle manure (according to Clemens et al., 2004).

Parameter		**Cattle manure undigested**	**Cattle manure digested 29 d**	**Cattle manure digested 50 d**
DM	[g kg^{-1}]	30.4	22.9	23.1
ODM	[g kg^{-1}]	22.0	14.5	14.3
COD	[g kg^{-1}]	37.3	21.7	19.7
N-Kj	[g kg^{-1}]	1.99	2.06	2.28
NH_4-N	[g kg^{-1}]	1.04	1.41	1.51

Advantages:

Recent studies show that anaerobic digestion seems to be an effective mitigation option for methane and greenhouse gas emissions from slurry stores. Schumacher (1999) and Wulf et al. (2003) show that the mitigation effect for cattle slurry is substantially higher compared to pig slurry. The study results of Wulf et al. (2003) show that anaerobic digestion reduces CH_4 emissions but enhances NH_3 emissions. Straw cover reduces NH_3 emissions but enhances (in particular for digested pig slurry) CH_4 emissions (Schumacher, 1999; Wulf et al., 2003). Amon et al. (2004) show that the production of NH_3 and N_2O but in particular of CH_4 is strongly related to slurry temperature and thus, under warm summer conditions, considerably more greenhouse gases were emitted than under cool winter conditions.

Disadvantages:

An improved manure application technique is needed, otherwise much of the benefit of abating during storage may be lost (see 2.10.1).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	→	↗

1.6.2 Application of digested slurry

Details of measure:

Fermented substrates differ from slurry in some of their chemical and physical parameters that might influence GHG emissions after application (Table 3). During anaerobic digestion methanogenic microorganisms producing CH_4 and CO_2 digest organic compounds from manure or co-substrates (grass and maize silage etc.). Nitrogen from this organic pool is transferred to inorganic nitrogen during this process so that the share of NH_4^+-N from nitrogen increases (Wulf et al., 2002a). Due to the higher NH_4^+-N content of fermented slurry the likelihood is given that NH_3 emissions increase after application compared to untreated slurry. In addition, constituents that can be oxidised by chemical or biological processes as well as dry matter content are reduced. Thus, due to the fermentation the consistency of the manure is changing (it turns into a thin fluid) so the rate of slurry infiltration into soil can increase.

After application, N_2O and NH_3 are the main gases emitted. Ammonia emissions after slurry application contribute to atmospheric N input in natural and nearly natural ecosystems, not only promoting soil and surface water acidification, eutrophication, and forest dieback, but also causing N_2O emissions. Therefore, ammonia is an indirect GHG and its global warming potential (GWP) can be expressed in terms of CO_2-equivalents.

Advantages:

Rubaek et al. (1996) reported similar or even lower NH_3 emissions loss from agricultural systems from fermented substrates compared with untreated slurry, whereas Kuhn (1998) postulates an increase of NH_3 emissions through slurry fermentation. Petersen (1999) showed in field experiments that anaerobically digested slurry induced lower N_2O emissions compared to undigested slurry. Clemens & Huschka (2001) showed the same in lab experiments.

Wulf et al. (2002b) showed that the influence of (co-)fermentation on N_2O and CH_4 emission was only small and of short duration, whereas the application technique had a much stronger effect (see 2.9.9, 2.10.1). In total, GHG emissions after field application from anaerobically treated substrates are similar to those from untreated slurry. Also Clemens et al. (2004) reported that fermentation of the slurry did not affect overall GHG emissions after application. Thus, these emissions need not to be included into the calculation.

Disadvantages:

Digested slurry has a higher pH which increases the risk for NH_3 emissions. It must be applied with improved application techniques, otherwise NH_3 emissions are likely to increase even if digested slurry infiltrates more rapidly into the soil. For the evaluation of the environmental effects of digested slurry application, it should be considered that due to the increase of NH_3 emissions also eutrophication and acidification effects could increase (Fangmeier et al., 1994).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	→	↗	→

1.6.3 Main factors affecting the efficiency of anaerobic digestion

1.6.3.1 Digestion and/or co-digestion

In digestion plants it is possible to use only manure as organic substrate whereas co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates such as residues from animal husbandry, plant production and directly produced energy plants or imported residues from the food industry (see 2.12.2.1).

Co-digestion of plant material and solid waste can provide an improved nutrient balance and therefore better digester performance and higher biogas yields and therewith in a higher reduction of GHG emissions. When manure is co-digested with easily degradable co-substrates such as energy crops or organic wastes, the efficiency of anaerobic digestion can be improved. The additional biogas collection can bring farmers a higher income.

Wrong nutrient ratios or co-substrates can change the digestion behaviour. Addition of unknown co-substrates or small amounts of inhibiting or toxic components can lead to process break-down with the necessity to dispose the digester content followed by a time consuming restart.

For co-digestion additional pre-treatment, mixing and hygienisation requirements can be needed. Hence, farmer know-how is required.
Co-digestion is economically critically dependent on crop costs and yield. Restrictions of land use for digestate must be considered.

1.6.3.2 Anaerobic digestion in cooler and warmer countries

Different heating conditions and needs of heat (and cooling) in warmer and cooler countries must be considered for all process steps of anaerobic digestion (fermentation, digestate storage etc.).
For manure that would otherwise be stored as liquid slurry, CH_4 emission reductions of 50 % are achievable in countries with cool climates. IPCC estimates a reduction in CH_4 emissions of up to 100 % dependent on the level of CH_4 recovery. According to Bates (2000) CH_4 emissions from liquid waste management systems in countries with warmer climates are more than 3 times higher; in these countries CH_4 emissions can be reduced by 75 %.
Hence, plant constructions in different European regions show considerable cost variation.

1.6.3.3 Farm scale or centralised digestion plants

Anaerobic digestion plants can be small scale (located on a farm) or large and centralised (e.g. from different farms). Any plant needs sufficient feedstock from the surrounding area without incurring excessive transport costs (both financial and environmental). For on-farm plants this is not an issue and there is no real limit on how small a digester can be. In practice, for commercial plants rather then self-built units, about 50 m^3 is the minimum viable size (according to 50 cattle). For centralised plants the maximum catchment area will be determined by local factors such as transport costs and the fuel value of the feedstock.
Financial and environmental advantages depend on circumstances of the chosen digestion plant etc.
The surrounding land of centralised digestion plants must have sufficient capacity to accept the nutrients in the digestate. For centralised plants, increased transport of manure leads to increased GHG emissions.

1.6.3.4 Use of power / power & heat / power & heat & cooling

In general, the cost-effectiveness and GHG mitigation efficiency of anaerobic digestion depends on the use of energy (use of power / power & heat / power & heat & cooling). It should be noted that an additional benefit of utilising biogas from anaerobic digestion plants to produce electricity, heat and cooling is that this will offset GHG emissions resulting from fossil fuel energy sources and this should be accounted for when considering the contribution of anaerobic digestion to wider GHG reduction.
Not all farms are able to use all produced heat for adjacent houses, hotels, manufactories etc. The usage depends on climatic and other conditions.
Plants to use heat for cooling are still in the development stage and are presently connected with high costs.

2 Measures on crop production

In general, Good Farming Practice is a requirement under EU Commission Regulation 1750/1999 and is an integral part of the Less Favoured Area Compensatory Allowance Scheme. It requires that farmers apply good farming practices compatible with the need to safeguard the environment and maintain the countryside. The three elements of Good Farming practice are legislation, verifiable standards and the Codes of Good Agricultural Practice and Training. Many of alternative mitigation strategies are related to tightening the nitrogen cycle of cropped ecosystems. Reducing N fertiliser use to provide greenhouse gas mitigation will require careful management of cover crops, residues, and the microbial and physical processes that regulate soil N availability.

Nitrogen Use Efficiency (NUE) refers to how well a crop uses available soil nitrogen. The more taken up and used by the crop, the less nitrogen remains in the soil to be leached, volatilised or denitrified to form nitrous oxides.

Nutrient management systems that strive to improve NUE do the following:

- make the required amount of available forms of nitrogen available when the crop needs them,
- place nitrogen where the crop roots can access them,
- reduce the amount of nitrate in the soil when the crop can not use it,
- account for and manage all sources of plant-available N,
- manage other cultural practices and conditions for NUE (e.g., soil and water management).

Benefits of improving NUE:

- reduce nitrous oxide production,
- increase carbon dioxide uptake by crops,
- increase yield and improve product quality,
- reduce fertiliser input and application costs - less energy and GHG produced for N-fertilisers,
- less run-off, groundwater contamination and N leaching.

Removing land from production provides maximum mitigation. This option may be practical for marginal land but less so for productive cropland that must meet the food needs of a burgeoning global population (Robertson et al., 2000).

2.1 Continuous plant cover (catch crops and intercrops)

Details of measure:

Catch crops are planted for use as forage or for green manuring for the following crop using, for example, the mulch seed technique. Catch crops are sown after the harvest of the main crop or into the main crop (intercrop) in order to minimise fallow periods or provide soil cover to improve mineral N accumulation (Mosier et al., 1996). Fertilisation of catch crops depends on the crop and the aim of cultivation. To ensure a dense plant stock and maximum uptake of nitrogen fertiliser, leguminous plants should not be cultivated. If legumes are used, they create aerial nitrogen (N fixation; see 2.8), which represents the cheapest biological nitrogen supply.

Catch cropping is used to reduce the nitrogen balance surplus in the following crop and therefore the subsequent nitrogen supply by green manuring or N fixation has to be taken into account when planning fertilisation for the following crop. For the maximum effect it should be ploughed into the soil as late as possible.

Advantages:

Winter or fallow cover crops can prevent the build-up of residual soil N, catching N that otherwise would be emitted as N_2O or leached (in particular during fall and winter) improving N use efficiency and soil quality.
The use of catch crops is also an option for carbon sequestration due to increased C inputs and lower decomposition rates (see 2.11).
In addition, a continuous plant cover by catch crops and intercrops prevents erosion by wind and water.

Disadvantages:

In most cases an additional operation is needed (not necessarily if the catch crop is sowed together with the crop - although it will be an extra cost for the seed and lower production).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	↗

2.2 Optimisation of water management (irrigation, drainage)

Details of measure:

On the one hand, a sustainable option to optimise the water management may be to match crop-growing patterns better to available water, rather than attempt to irrigate - although, in many European regions additional irrigation is inevitable (maximum N_2O emissions are reported shortly after irrigation or rainfall; Granli & Bockman, 1994).
On the other hand, excess water in the crop root zone soil is injurious to plant growth. Crop yields are drastically reduced on poorly drained soils, and, in cases of prolonged water logging, plants eventually die due to a lack of oxygen in the root zone. In such a case, for water table management the control by drainage is needed (see 1.3.6). Excess soil water is removed from fields using surface or sub-surface drainage features. Tile drainage (one of the most common forms) is established at prescribed depths and spacings to transfer water safely to a proper outlet. Optimised irrigation and drainage can prevent large groundwater fluctuations or flooding.

Figure 16: Irrigation system.

Advantages:

Irrigation and drainage management is a potential way of controlling emissions. If a soil is wetted to produce anoxic microsites, and then dries within 24-72 hours, insufficient time will have elapsed for N_2O reductase to be generated, preventing N_2O reduction to N_2. Thus, the N_2O emission factor of poorly and imperfectly drained soil can be reduced considerably.

Due to optimised water conditions for plants, yield can be improved (increase of yield amount or quality) so that GHG emissions are reduced per product unit.

Disadvantages:

Improved drainage is likely to increase nitrate leaching and thus indirect N_2O emissions (depending on N input, soil texture etc.). The drainage of organic soils (former wet peat lands) can result in increased GHG emissions (a small CH_4 emission is changed to a large CO_2 and N_2O emission). A high groundwater level will decrease GHG emissions from this type of soil, common in northern Europe. Manipulating irrigation to control emissions would be likely to have adverse effects on crop growth and labour requirements, and the scarcity of reliable data mean that realistic assessments are not possible.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↘	→	↘

2.3 Prevention of soil compaction

Details of measure

Soil compaction is estimated to be the cause of degradation of 33 million hectares of agricultural land only in Europe. Compacted subsoil is not optimal, both from an economic and an environmental point of view. It results in lower yields and quality of the crop and requires an increased supply of water, nutrients and energy to treat the soil. In addition, soil compaction increases denitrification (Motz & Kutzbach, 2002) and so can increase N_2O emissions. Wet soil has less resistance to compaction.

There are many options to avoid soil compaction:

- avoid wheel traffic, use wider tires, dual tires, tracks,
- maintain minimum tire inflation,
- avoid tillage of wet soils,
- minimise tractor weight, avoid oversized equipment,
- combine field operations,
- add organic matter to the soil,
- vary the depth of primary tillage,
- use tractors with four-wheel drive or mechanical front wheel drive.

Advantages:

McTaggart et al. (1997) found that N_2O emissions from compacted grassland soil were clearly higher than those from uncompacted soil.

Oenema et al. (1997) suggested that although data on the effect of soil compaction on N_2O emissions are limited, treading by cattle could easily increase N_2O emissions from grassland soil.

Disadvantages:

Sometimes soil compaction is difficult to control or to influence.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	↗

2.4 Reduced tillage or no-tillage

Details of measure:

Sowing a crop without prior cultivation and with very little soil disturbance at seeding (reduced and no-till or zero-till, direct drilling etc.) reduces additional operations such as ploughing. In general, crop yields are equal for conventional and no-till systems provided that weeds are controlled and proper crop stands obtained (Norwood, 1994; Miller & Nalewaja, 1985).

Advantages:

Smith et al. (2000) suggest that when the potential increases of N_2O production are converted to carbon equivalents and included in the calculation, the total mitigation effect in terms of the GWP is significantly reduced compared to when only soil carbon sequestration is considered (see 2.11.3).

Furthermore, no-till with retained stubble has the potential to improve soil properties and increase sustainability. It can do this by lifting and modifying soil biological activity which gives excellent improvements in all aspects of soil fertility, being, physical, chemical and biological. These improvements lead to better farm management and sustainability. The main benefits of no-till, with appropriate agronomic management, include:

- almost no soil erosion through stubble retention and proper grazing management (especially in sandy soils; Bilbro & Fryrear, 1994),
- greater flexibility of farm operations through less time used at seeding and improved soil structure leading to better trafficability,
- more precise seed placement with more even crop emergence, if seeded at correct moisture content,
- more water harvested to grow the crop in dry areas (Crutchfield et al., 1986),
- often less in-crop weed, less labour, fuel and machinery costs per hectare, and
- consequently, better whole farm profitability and sustainability.

Moreover, less fossil fuel would be used which significantly reduce GHG emissions from fossil fuel use from operations.

Disadvantages:

However, when considering zero tillage, as well as when considering any land management change, the likely effect on other, non-CO_2 greenhouse gases needs to be considered. Recent studies have shown that as much as one half of the mitigation effect attributable to carbon sequestration under zero tillage can be reversed by an increase in N_2O emissions.

N_2O emissions may increase, as soils may become more anaerobic and advance denitrification under no-till.

Successful conservation agriculture, regardless of definition, is highly dependent upon effective weed control. Therefore, this measure can be connected with high initial machinery costs and associated with increased pesticide usage and its negative environmental side effects.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.5 Precision farming

Details of measure:

Precision farming is the title given to a method of crop management by which areas of land/crop within a field may be managed with different levels of input depending upon the yield potential of the crop in that particular area of land.

Precision farming is an integrated agricultural management system incorporating several technologies. The technological tools often include the global positioning system (GPS), geographical information system (GIS), yield monitor, variable rate technology, and remote sensing.

The goal of precision farming is to gather and analyse information about the variability of soil and crop conditions in order to maximise the efficiency of crop inputs within small areas of the farm field. To meet this efficiency goal the variability within the field must be controllable. Efficiency in the use of crop inputs means that fewer crop inputs such as fertiliser and chemicals will be used and placed where needed (see 4.1.4). The benefits from this efficiency will be both economical and environmental.

Advantages:

The benefits of precision farming are 1) the cost of producing the crop in that area can be reduced and, 2) the risk of environmental pollution from agrochemicals applied at levels greater than those required by the crop can be reduced, reducing GHG emissions from prechains and crop production.

Disadvantages:

The precision farming techniques are only financially feasible for bigger farms or contractors (in the case of contractors also applicable for smaller farms).

Sufficient know-how of the farmer is needed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

2.6 Changing from winter to spring cultivars

Details of measure:

Spring-sown crops have lower nitrogen requirements due to the shorter growing period and lower yield potential as compared to winter-sown crops. Thus, changing from winter to spring cultivars would reduce the quantities of nitrogen applied to the crop and has potential to reduce N_2O emissions.

Advantages:

For spring barley, an average recommendation for fertiliser-N application to spring barley would be 30 kg ha^{-1} less than for winter barley; for oilseed rape the difference would be 40 kg ha^{-1}. The N_2O emissions from soil after fertiliser application as well as GHG emissions from fertiliser production and transportation can be reduced.

Disadvantages:

In practice the potential benefits for N_2O emissions from spring cultivars may be outweighed by the potential environmental problems of bare land over the winter period, or land being used for livestock feeding, and likely increases in nitrate leaching and N_2O emissions from crop residues and soil N during autumn and winter if not combined with a catch crop. If additional catch crops were seeded this would increase the costs and GHG emissions for the additional operation.

Furthermore, the reduced fertiliser input to spring cultivars would be outweighed by the reduced yield of e.g. spring wheat in comparison to winter wheat, so that relating to the product unit (kg wheat) the total GHG emissions will not decrease.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	→	↘	→

2.7 Breed cultivars that improve N use efficiency

Details of measure:

N-use efficiency is defined as the ability of a genotype to produce superior grain yields under low soil N conditions in comparison with other genotypes (Graham, 1984; Sattelmacher et al., 1994). Experiments with the U.S. Corn-Belt (Balko & Russell, 1980), tropical (Lafitte & Edmeades, 1994; Bänziger et al., 1997), and European maize (Bertin & Gallais, 2000) indicated that genotypes could differ considerably in their N-use efficiency. Hence, breeding for adaptation to low soil N seems feasible.

Advantages:

If fertiliser nitrogen (including manure nitrogen) is better used by the crop, less N_2O will be produced and less nitrogen will leak from the system.

Studies on feeding dairy cows high sugar grasses showed that these grasses resulted in reduced N excretion rates to the environment (IGER, 2001) (see 1.3.4). These grasses also contained less plant protein but, due to a better balance between energy and protein, supply animal performance was not affected. Under some conditions these grasses even increased milk yield. The results suggested that the high sugar grasses reduced the feed N loss to the environment by about 24 %. This confirms that breeding of other cultivars can be successful.

Disadvantages:

Research is in its infancy and is a time-consuming process.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

2.8 Use of N fixing crops

Details of measure:

The symbiotic nitrogen fixation (converted from N_2 to a reactive form of N) of crop production (legumes or clover) provides an important input of N to the soil (see 1.3.5). For crop production, N fixation is primarily important to the growth of legumes (like peas, beans, soybean, alfalfa and sometimes clover), many of which form symbioses with specific bacteria, generically termed rhizobia. The *Rhizobium* bacterium "infects" a root hair of a legume (such as alfalfa) and the root hair wraps around the bacterium, creating a nodule on the root. The bacterium trapped inside the nodule continue to multiply and fix N_2.

Worldwide, biological N_2 fixation is estimated at 145 to 200 million tons per year, compared to approximately 90 million tons per year of world fertiliser use (Havlin et al., 1999).

Organic systems rely exclusively on organic fertilisers and N_2 fixation for N inputs, and so N supply in this system is much more dependent on the slow release of organic N from manure and crop residues from previous crops than is the case for conventional systems with application of inorganic fertilisers. The likely increased competition between plants and microbes for available N could significantly alter the pattern of N turnover in organically managed soil.

Advantages:

On average, biological nitrogen fixation supplies 50-60 % of the N harvested in grain legumes and 70-80 % of the N accumulated by pasture legumes (Danso, 1995).

Disadvantages:

Because of the uncertainty in knowing the amount of gaseous nitrogen fixed during N fixation (Peoples et al., 1995) and the lack of country data on N-fixing crops, it is difficult to assign a conversion factor to nitrous oxide emission that is related to the amount of N fixed by a crop. For the input of N in biological fixation, this probably leads to double counting, since the N-fixation takes place inside the plants, and the N that contributes to N_2O emissions is the N made available to the soil microorganisms. This soil N from N fixation is counted in either crop residues or manure (Olesen & Petersen, 2002).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↑

2.9 Slurry, manure and fertiliser management

2.9.1 Soil analysis

Details of measure:

Profitable use of fertiliser is only possible when a farmer knows how much is really needed, and that is only possible if they know how much a soil can already supply. Routine soil analyses include soil acidity (pH), lime requirement, available calcium, available magnesium, available phosphate, total nitrogen and organic matter. A detailed analysis of soil N_{min} (NH_4^+-N, NO_3^--N) additionally helps to identify the nutrient demand of the crops. Soil analyses are used to more effectively target fertiliser and animal manure applications, which can quickly impact the benefit of production economics and also environmental protection.

Advantages:

Soil N-tests can reduce over-fertilisation of crops and reduce needless fertiliser production, which significantly reduces total GHG emissions.

Disadvantages:

Soil analyses are connected with costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

2.9.2 Manure analysis

Details of measure:

Supply planning starts with an inventory of the nutrients produced on the farm. Animal manure is an important source of nutrients. The quantity of manure collected and stored, either dry or liquid should be determined. Nutrient content of animal manure is variable, depending on the type and age of animal, feed source, housing type, handling method, temperature, and moisture content. Because of this variability in nutrient content, individual land application decisions should be based on the nutrient content of the manure to be applied. The nutrient content of slurry can also vary considerably within a store due to settlement and crusting. Similarly, the composition of solid manure in a heap can vary depending on the amount of bedding and losses of nutrients during storage.

A manure sample (especially solid manure) should be analysed for dry matter, total nitrogen, ammonium-N, phosphorous, potassium, sulphur and magnesium.

Although manure application rates are usually based on N availability, managing manures for their P_2O_5 and K_2O contents can also be important. The availability of P_2O_5 and K_2O in manures in the year of application is similar to that of fertiliser sources, so basing application rates on the manure's P_2O_5 and K_2O content should be adequate. The amount of applied P_2O_5 and K_2O in the manure should be determined and supplemented with mineral fertiliser, if necessary. On soils testing high in P_2O_5 and K_2O (no P_2O_5 and K_2O recommended from soil test), it should be considered to use the manure on other fields requiring P_2O_5 and K_2O (see 2.9.2).

Advantages:

With the information of the manure analysis (and soil analysis; see 2.9.1), and knowledge of the nutrient levels of the manure, economically and environmentally sound application rates for both manure and fertiliser can be determined. Analysis of manure prevents over/under application, which increase productivity and/or reduces nutrient losses and GHG emissions.

Disadvantages:

Manure analyses are connected with costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	↗

2.9.3 Adaptation of fertilisation and pesticide application on demand

Details of measure:

To optimise fertilisation management and to minimise environmental impacts due to organic fertilisation it is necessary to evaluate the amount of fertiliser based on the physiological nutrient uptake of crops (and grassland; see 1.3.2). Therefore, the nutrient supply (N, P, K, Ca, Mg etc.) must be synchronised with the crop demand.

A nutrient budget is the comparison between all sources of nutrients available to the farmer and the requirement of nutrients to meet the crop and soil needs. The sources can either be from on the farm, such as livestock manure or credits from legumes, or from off the farm, such as purchased fertiliser. The requirement is the amount of nutrients needed by the crop to obtain the expected yields.

Most values of nutrient availability from different sources and plant nutrient requirements are based on long-term historical averages and grassland/pasture research; i.e. both the nutrient requirements and availability are based on climatic and soil condition of the past. These values are given with some surety that the plants grown will be supplied with adequate amounts of nutrient during the growing season. All environmental losses, such as run-off and leaching, have been accounted for. Climatic conditions, particularly temperature and soil moisture, greatly influence both the crop performance and the soil's capacity to provide nutrients to the plant. During any growing season the climatic conditions may affect both the plant growth and soil delivery of nutrients to the plant. Although a nutrient budget is not an exact formula for supplying nutrients, it is one method for organising the nutrient needs of the crop with the nutrients available on the farm. Nutrient budgets can easily determine if there is a gross imbalance between the nutrients that are available vs. the amount required. Nutrient budgets are one of the best methods to see the overall supply of crop nutrients available compared to the estimated crop needs as given by historic records and field research. Continued use of soil testing (see 2.9.1), plant and manure analyses (see 2.9.2), and yield monitoring are essential to maintain a good nutrient balance with desired results.

It is also part of Good Farming Practice that pesticides are only applied if defined threshold values are exceeded.

The ideal supply of nutrients or treatment with pesticides is given in the framework of a fully developed precision farming system (see 2.5).

Advantages:

By fertilisation on demand, soil nutrient depletion on the one hand and on the other hand nutrient excess, leading to leaching is avoided. This increases the productivity of the whole farm and thus significantly decreases the GHG emission per product units.

Disadvantages:

This measure is already part of existing Good Practice Guidelines.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↑	↗	↑

2.9.4 Matching the type of fertiliser to seasonal conditions

Details of measure:

Fertilisers can comprise up to 30 % of farm expenditure, so it is important to use the right quantity and product. The higher the crop's potential, the greater is its nutrient requirement. Seasonal forecasts can be useful when determining a flexible nitrogen fertiliser strategy. Having a better understanding of the timing and amounts of rainfall and their impact on potential yield will allow growers to take advantage of different growing season conditions. Soil organic N is found in several different forms, which are not equally able to release plant-available N. Understanding the dynamics of each type of N should lead to better predictions of mineralisable N (see 2.9.6).

Under wet conditions, emission of N_2O from NO_3^--containing fertilisers is often higher than from fertilisers containing only NH_4^+ (Clayton et al., 1997). Therefore, for wet conditions, a fertilisation strategy in which fertiliser containing only NH_4^+ instead of the commonly used NO_3^- fertiliser are applied, may be an appropriate option to mitigate N_2O emission from intensively managed arable land or grasslands.

Advantages:

Avoiding NO_3^- during wet seasons and NH_4^+ during dryer seasons may give lower NH_3 and N_2O emission (Clayton et al., 1997).

Disadvantages:

It is not always achievable to adapt the fertiliser application to an entire growing season.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

2.9.5 Optimisation of split application schemes

Details of measure:

In most cases, nitrogen fertiliser is the most costly major nutrient in any fertiliser programme. By placing all the nitrogen requirements at seeding, a producer must rely on adequate rainfall during the growing season so the crop can efficiently utilise the nitrogen. Split application is the process of matching nitrogen supply for a preestablished target yield and a given level of soil moisture, and then supplying the remaining nitrogen as moisture conditions improve.

Splitting the total nitrogen requirement of the crop over multiple applications increases N fertiliser use efficiency by different rates of N fertiliser through improved timing of N fertiliser application. Sometimes several split applications of N are needed to achieve an N supply that approximates plant demand.

Advantages:

Split applications of nitrogen give producers greater flexibility in their fertiliser programme. This practice minimises the risk of placing all the nitrogen at the time of seeding. By providing nitrogen to meet the changing demands of a growing crop, producers can potentially increase nitrogen use efficiency. Split application reduces the exposure of nitrogen in saturated soils where the potential for losses such as leaching and denitrification are increased. It also reduces the amount of product. Finally, proper timing and placement of nitrogen may help reduce nitrous oxide emissions.

Therefore, applying nitrogen fertiliser in more than one application during the growing season could increase forage/crop production and so reduce total GHG emissions relative to product unit.

Disadvantages:

Several studies suggest that a split application N management strategy is not necessary to obtain optimum grain yields and grain protein.

For split application, more operations are needed, which increases the soil compaction and use of fossil fuels.

Split application of nitrogen fertiliser is more an option for intensive management situations.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	↘	↗

2.9.6 Consideration of fertiliser types

Details of measure:

Although it is generally agreed that fertilisers come in three physical forms (liquid, solid and gas), there are actually only two classes of fertilisers: liquid and solid (granular). Anhydrous ammonia (NH_3) is a gas, but it is classified as a liquid because it is a liquid under pressure. But N is mostly applied as urea, NH_4^+-N or NO_3^--N.

Generally, application of urea increases the NH_3 emissions but reduces the N_2O emissions whereas NO_3^--N fertilisation reduces NH_3 emissions but increases N_2O emissions and leaching (see 2.9.4).

The following main fertiliser types are actually on market:

- Urea is the most concentrated solid nitrogen fertiliser (46 % N). The availability of nitrogen for plant uptake can be delayed, particularly in cold spring weather, because urea must be transformed into ammonium and to the final nitrate form. This chemical transformation is dependant on temperature and soil humidity.

- Ammonium sulphate has relatively low nitrogen content (21 %, all in the ammonium form). It also, however, contains 24 % sulphur, another essential plant nutrient.
- Calcium ammonium nitrate (CAN) is a mixture of ammonium nitrate and a minimum of 20 % calcium/magnesium carbonate. Its nitrogen concentration ranges from 25 % to 28 %. Half of the nitrogen is in the nitrate form, which is immediately available to plants, and the other half is in the ammonium form. Ammonium nitrate based fertilisers are well suited for most soils, crops and climatic conditions.
- Ammonium nitrate (AN) is another concentrated source of nitrogen (33.5-34.5 % N). AN fertilisers account for 21 % of total fertiliser nitrogen in Western Europe and it is the most commonly used nitrogen fertiliser in France (38 %) and in the UK (68 %).
- The most typical liquid formation is made using 50 % urea and 50 % ammonium nitrate in water (urea/ammonium nitrate, UAN) to form a fully dissolved clear liquid fertiliser (28-32 % N). UAN offers farmers the advantage of reduced manual handling but it requires special storage facilities and equipment for transport.
- Ammonium sulphate nitrate is a combination of ammonium sulphate and ammonium nitrate (typical grade: 26 % N, containing 7.5 % as nitrate, 18.5 % as ammonium, with 14 % S).
- Calcium nitrate, which contains 14.4 % N in nitrate form and 19 % water-soluble calcium, is a form of nitrogen particularly suited for fast growing market-garden crops and for fruit trees due to its quick action.
- Sodium nitrate, Chilean nitrate and calcium cyanamide are used in small volumes on special crops.

Advantages:

Depending on climate, soil etc. conditions the diverse fertiliser types have different potential to reduce losses by leaching and GHG (N_2O, NH_3) emissions.

Disadvantages:

The emissions of one GHG can be reduced whereas the emissions of another GHG can increase. Ammonia is not a direct GHG in itself but gives rise to N_2O secondarily.
The reduction of N_2O depending on different fertiliser types is of short effect. Primarily added N in the ecosystem can give an increased background emission over decades (Bakken & Bleken). Use of a fertiliser type can give lower N_2O emissions in the first year, but it is possible that it will not change the overall GHG emission.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

2.9.7 Slow and controlled release fertilisers and fertilisers with nitrification or urease inhibitors

Losses through immobilisation, denitrification, volatilisation and leaching may occur especially with nitrogen. Consequently, it has been the aim of science and the fertiliser industry to develop special types of fertilisers avoiding or at least reducing such losses, in addition to the production of conventional nitrogen-containing fertiliser types (ammonium sulphate, ammonium nitrate, calcium ammonium nitrate, ammonium sulphate nitrate, urea, DAP, and NP and NPK fertilisers) (Joly, 1993; Trenkel, 1997).
These special types can be listed as:

- slow-release and controlled-release coated/encapsulated fertilisers,

- nitrification and urease inhibitors or stabilised fertilisers (fertilisers associated with nitrification or urease inhibitors).

Shoji & Gandeza (1992) consider that an ideal fertiliser should have at least the following three characteristics:

- it should only need one single application throughout the entire growing season to supply the necessary amount of nutrients for optimum plant growth,
- it should have a high maximum percentage recovery in order to achieve a higher return to the production input, and
- it should have minimum detrimental effects on soil, water and atmospheric environments.

Slow, and particularly controlled-release as well as 'stabilised' fertilisers can meet these requirements for an ideal fertiliser to a considerable extent.

2.9.7.1 Slow and controlled-release fertilisers

Details of measure:

The delay of initial availability or extended time of continued availability of slow and controlled-release fertilisers might occur by a variety of mechanisms. These include controlled water solubility of the material (by semipermeable coatings, occlusion, or by inherent water insolubility of polymers, natural nitrogenous organics, protein materials, or other chemical forms), by slow hydrolysis of water-soluble low molecular weight compounds, or by other unknown means (Figure 17; AAPFCO, 1995). For example, polyolefin-coated fertilisers are a type of controlled-release fertiliser where fertiliser granules are covered with a thermoplastic resin. The release of the N fertiliser is temperature-dependent and is not controlled by hydraulic reactions or microbial attack of the coating.

Advantages:

The use of controlled-release fertilisers may improve N-use efficiency by matching nutrient release with crop demand, reducing NO_3^--leaching and denitrification losses (N_2O). Many of the results presented by Minami (2000) showed that controlled-release fertilisers were useful for the reduction of N_2O emission from fertilised soils.

Less field operations are needed, which reduces costs and environmental side-effects.

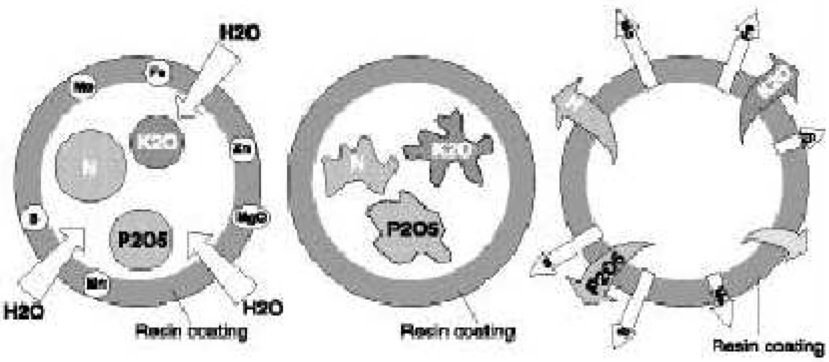


Figure 17: Mode of action of a coated/encapsulated controlled-release fertiliser (Source: Hähndel, R.; BASF AG, 1997).

Disadvantages:

However, further information is needed to evaluate the decrease of N_2O emissions from ammonium compound fertilisers.

This type of fertiliser is more expensive compared to conventional fertilisers and thus is more used in horticulture than in agriculture.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.9.7.2 Nitrification and urease inhibitors

Details of measure:

Nitrification inhibitors are compounds that delay bacterial oxidation of the ammonium-ion (NH_4^+) by depressing over a certain period of time the activities of *Nitrosomonas* bacteria in the soil. They are responsible for the transformation of ammonium into nitrite (NO_2^-) which is further changed into nitrate (NO_3^-) by *Nitrobacter* and *Nitrosolobus* bacteria. The objective of using nitrification inhibitors is, therefore, to control leaching of nitrate by keeping nitrogen in the ammonia form longer, to prevent denitrification of nitrate-N and thus N_2O emissions and to increase the efficiency of nitrogen applied (Trenkel, 1997; Weiske et al., 2001).
Urease inhibitors prevent or depress over a certain period of time the transformation of amide-N in urea to ammonium hydroxide and ammonium. They do so by slowing down the rate at which urea hydrolyses in the soil, thus avoiding or reducing volatilisation losses of ammonia to the air (as well as further leaching losses of nitrate). They increase the efficiency of urea and nitrogen fertilisers containing urea (e.g. urea ammonium nitrate solution UAN). Urease inhibitors thus inhibit for a certain period of time the enzymatic hydrolysis of urea, which depends on the enzyme urease (Farm Chemicals Handbook '96, 1996). Thus, urease may reduce N leaching and N_2O emissions from nitrification but in particular from denitrification.
Actually, there are only two nitrification inhibitors licensed in Europe (dicyandiamide, DCD; 3,4-dimethyl pyrazole phosphate, DMPP). Inhibitors can be used for mineral fertilisers and with slurries.

Advantages:

Fertilisers with nitrification and urease inhibitors can reduce NH_3 and/or N_2O emissions by controlling the nutrient supply (conserve the applied NH_4-N as NH_4^+), by delaying the nitrification process and thus N_2O emissions from nitrification and by delaying the formation of nitrate and thus significantly reducing N_2O from denitrification (Granli & Bockman, 1994; Mosier et al., 1996; Dittert et al., 2001; Weiske et al., 2001).

Disadvantages:

The costs of fertilisers with urease and nitrification inhibitors are higher in comparison to usual fertilisers (but the higher yield can compensate the additional costs). At present slow release products are more commonly available and used within the horticultural sector, as much greater value of some horticultural crops justifies the use of these more expensive products.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.9.8 Substituting inorganic by organic nitrogen fertiliser

Details of measure:

A reduction (e.g. by limits) of the application of inorganic fertiliser in arable and grassland systems can reduce the total amount of nitrogen in the systems by replacing inorganic nitrogen from manure (AEA Technology Environment, 1998; Hendriks et al., 1998). This implies a more efficient use of manure that is otherwise disposed of as waste products (Hendriks et al., 1998).

Advantages:

Emissions of N_2O as well as emissions of NH_3 will decrease because of a reduction in the use of synthetic fertilisers. AEA Technology Environment (1998) reported that a limit on inorganic fertiliser application on cereals and grassland of 50 kg per ha would result in a clear reduction of synthetic fertiliser use and associated N_2O emissions.

The reduced production of synthetic fertilisers could significantly reduce total prechain GHG emissions.

Disadvantages:

Synthetic fertilisers better meet the demand of plants and have in some models a lower emission factor in comparison to the applied N amount. Also losses by N leaching are higher for manure compared to mineral fertiliser.

The transporting of additional manure to other farms results in increased emissions from transport.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	↗	→	↘

2.9.9 Application of digested slurry

Details of measure:

Fermented substrates differ from slurry in some of their chemical and physical parameters (Table 3) that might influence GHG emissions after application (see 1.6, 1.6.1, 1.6.2). During anaerobic digestion methanogenic microorganisms producing CH_4 and CO_2 digest organic compounds from manure or co-substrates (grass and maize silage etc.). Nitrogen from this organic pool is transferred to inorganic nitrogen during this process so that the share of NH_4^+-N from nitrogen increases (Wulf et al., 2002a). Due to the higher NH_4^+-N content of fermented slurry the likelihood is given that NH_3 emissions increase after application compared to untreated slurry. In addition, constituents that can be oxidised by chemical or biological processes as well as dry matter content are reduced. Thus, due to the fermentation the consistency of the manure is changing (into a thin fluid) so that the rate of slurry infiltration into soil can increase.

After application, N_2O and NH_3 are the main gases emitted. Ammonia emissions after slurry application contribute to atmospheric N input in natural and nearly natural ecosystems, not only promoting soil and surface water acidification, eutrophication, and forest dieback, but also causing N_2O emissions. Therefore, ammonia is an indirect GHG and its global warming potential can be expressed in terms of CO_2-equivalents.

Thus, the technique to apply digested slurry is of substantial importance for the rate of NH_3 and N_2O emissions after application.

Advantages:

Rubaek et al. (1996) reported similar or even lower NH_3 emissions loss from agricultural systems from fermented substrates compared with untreated slurry, whereas Kuhn (1998) postulates an increase of NH_3 emissions through slurry fermentation. Petersen (1999) showed in field experiments that anaerobically digested slurry induced lower N_2O emissions compared to undigested slurry. Clemens & Huschka (2001) showed the same in lab experiments.

Wulf et al. (2002b) showed that the influence of (co-)fermentation on N_2O and CH_4 emission was only small and of short duration, whereas the application technique had a much stronger effect (see 2.10.1). The experiments showed that indirect N_2O production from emitted NH_3 might contribute a great proportion to GHG emissions from organic fertilisation. Therefore, NH_3 measurements should be included in experiments designed to evaluate emissions of greenhouse gases. For spreading co-fermented slurry on grassland, trail shoe application seemed to be the best way minimising trace gas emissions (Wulf et al., 2001; Wulf et al., 2002b). On arable land, trail hose application with immediate harrowing seems to be recommendable, as in addition to the mentioned sources of greenhouse gases, injection of slurry causes higher fuel consumption with negative effects on GHG budgets. In total, GHG emissions after field application from anaerobically treated substrates are similar to those from untreated slurry (Wulf et al., 2002b). Also Clemens et al. (2004) reported that fermentation of the slurry did not affect overall GHG-emissions after application.

Disadvantages:

Digested slurry has a higher pH which increases the risk for NH_3 emissions. It must be applied with improved application techniques, otherwise NH_3 emissions are likely to increase even if digested slurry infiltrates more rapidly into the soil. For the evaluation of the environmental effects of digested slurry application it should be considered that due to the increase of NH_3 emissions also eutrophication and acidification effects could increase (Fangmeier et al., 1994).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
→	→	↗	→

2.9.10 Timing of application

Details of measure:

Maximum fertiliser efficiency is achieved by applying manure and the right mineral fertilisers containing the appropriate proportions of different nutrients at the correct time for the specific crop and soil (see 2.9.3, 2.9.4, 2.9.5, 2.9.6, 2.9.7). Therefore, the timing of applications of manures and fertilisers to land must be in synchrony with active crop growth to maximise crop uptake of nutrients. Emissions (NH_3-N) are highest under warm, dry, windy conditions. Emissions can be reduced by choosing the optimum time of application, i.e. for cool humid conditions, in the evening, before or during rain (consideration of soil compaction; 2.3) and by avoiding spreading during June, July and August. Due to the fact that main NH_3 losses occur in the first hours after application a manure application in the evening is to favour compared to the morning. Application during late fall and winter should also be avoided to reduce N leaching and N_2O emissions from denitrification and whenever possible prior to anticipated rainfall to reduce nutrient loss, run-off, soil compaction and tile effluent (see 2.9.4, 2.9.6).

Advantages:

In general, an optimised timing (and placement; see 2.9.11) of application maximises both the crop uptake of nutrients and yield, thereby increasing net profit for the producer.

N_2O emissions from fertiliser are significantly reduced by avoiding fertiliser applications during wet periods or after (heavy) rainfall or snowsmelt. Menzi et al. (1998) showed that the postponement of the application date from 6th June to the morning of the 10th June results in a substantial NH_3 emission reduction. Also Frick & Menzi (1997) showed that the application of slurry at 20:00 of a warm day in August reduced the NH_3 emissions clearly compared to the application at noon and considerably compared to the application at about 6:00.

Better use of manure nutrients leads to a reduction of mineral fertiliser input.
Such emission reductions can be achieved at no or low costs.

Disadvantages:

The best moment to apply manure is not always easy to find.
It is difficult to quantify the reduction potential of comparable methods (especially to find the right reference).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↑

2.9.11 Fertiliser placement (band placement)

Details of measure:

Fertiliser placement is one of the tools that a producer can use to improve the efficiency of fertiliser use. Efficiency of both N and P is normally increased when the fertiliser is placed in a concentrated band in the soil. For both N and P, minimising the contact between the soil and the fertiliser slows the reactions of the fertiliser in the soil and reduces its loss, but the diffusion rates vary between nutrients (nitrate>ammonium>phosphate). Nutrient uptake occurs either by mass flow (about 15-30 % for nitrogen) or by diffusion (almost 100 % in the case of phosphorus).

A goal of fertiliser placement is to maximise root-nutrient contact, especially at the early stages of crop/root development, without causing emergence or establishment problems. The importance of fertiliser placement is often related to phosphorus, since its movement in soil is very slow, especially in cold conditions, usually only a few centimetres over several months. As with phosphorous, efficiency of nitrogen fertiliser is generally increased by band placement. However, the reasons for the increase in efficiency are different for N as compared to P. Nitrogen fertiliser supplies N in the form of ammonium, nitrate, urea or as a blend of these ions. The ammonium ions will be converted by microorganisms in the soil to form nitrate through nitrification, if the soil is warm enough for microbial activity (the rate of conversion will increase as soil temperature increases). Ammonium sources are readily lost by volatilisation when left on the soil surface, so banding ammonium or ammonium producing sources below the soil surface reduces volatilisation losses. But, once in the soil, nitrogen is more readily lost from the nitrate form than the ammonium form. Both ammonium and nitrate can be incorporated into the organic component of the soil through immobilisation by soil microorganisms, but nitrate is more mobile in the soil and can also be lost by leaching below the rooting zone. Nitrate is also subject to losses by denitrification, the conversion of nitrate to nitrogen oxides which get lost to the atmosphere. Placing the fertiliser in a band reduces the contact between the fertiliser and the soil microorganisms, reducing immobilisation. Banding also slows the conversion of urea to ammonium and of ammonium to nitrate. This can reduce losses by denitrification and leaching.

As placement of nutrients close to the root system can improve the efficiency of nutrients, different fertiliser placement techniques are used. Granular fertiliser can be broadcast (surface applied), broadcast-incorporated ('plowdown'), surface banded, or deep banded. Liquid fertiliser can be broadcast, banded with either a point ('spoke') injector, shank, or dribble applicator, or applied to the growing plants (foliar application or fertigation). Banding can be performed prior to seeding, with/near the seed ('starter' or 'pop-up'), or after planting.

Advantages:

It has been demonstrated that plant uptake of fertiliser nitrogen can be improved, and total nitrogen losses reduced from the levels achieved with surface broadcasting, by incorporation or deep placement of the nitrogen fertiliser (Rees et al., 1997). Placement of the nitrogen deep in the soil in an anaerobic zone will lower the N_2O/N_2 ratio when denitrification occurs. Placement beneath the soil (e.g. at a depth of 7-8 cm together with the seed) also decreases ammonia volatilisation by providing a physical barrier in the form of a layer of soil to trap any ammonia liberated. Rees et al. (1997) found that improved fertiliser placement could considerably increase the recovery of fertiliser nitrogen. Relative recoveries and level of nitrogen loss can also be influenced by fertiliser composition, and the rate and timing of application (Strong et al., 1991; McTaggart et al., 1994; Smith et al., 1997).

Fertiliser banding can increase N use efficiency and yield by as much as 15 %.

Also foliar fertilisation represents an alternative means of applying supplementary nitrogen during periods of rapid plant growth and nitrogen demand, or at times of critical physiological stress. Its greatest use has traditionally been with high-value crops such as fruits and vegetables, although it has been successfully used for late applications of nitrogen to cereal, leguminous and fibre crops to either increase grain protein or yield (Smith et al., 1991). As urea is rapidly absorbed it is commonly used for foliar applications of nitrogen. In wheat, around two-thirds of foliar applied urea-nitrogen was incorporated into plants within four hours of application, and almost 80 % of the nitrogen applied was recovered in grain at the final harvest (Smith et al., 1991). Direct measurements of gaseous emission in such systems showed that very little nitrogen was lost from foliar applied urea unless rainfall washed unassimilated urea from the plant on to the soil (Smith et al., 1991).

Disadvantages:

N_2O emissions (denitrification) and N leaching may increase when added N is incorporated under the soil surface, especially during wet conditions.

Large differences in yield and quality are generally not expected to be influenced by varying N fertiliser placement methods because nitrate is mobile in soils.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

2.9.12 Increasing rate of infiltration into soil

2.9.12.1 Dilution of manure

Details of measure:

Dilution of manure/slurry with water or applying treated manure (anaerobic digestion, see 1.6.2, 2.9.9; slurry separation, see 1.2.11) reduces the slurry dry matter content and thus increases the rate of infiltration into soil (see 2.9.12.2).

An alternative for farmers would be to disturb the soil surface of heavier land (e.g. through harrowing) prior to spreading to facilitate infiltration or to spread onto recently cultivated land, in order to reduce methane emissions and minimise other forms of pollution (Chadwick & Pain, 1997).

Advantages:

Using a ratio of water to manure to 1:2 or even 1:1 reduces NH_3 emissions (Menzi et al., 1997; Beudert et al., 1988).

Rapid infiltration of slurry into the soil encourages microbial oxidation of methane.

Disadvantages:

Dilution of manure is connected with higher application amounts and thereby with higher energy expenses (transports, costs), extra storage capacity, a greater risk of surface run-off, leaching and N_2O emissions (denitrification of leaching nitrate).

Due to the higher moisture content, an increase in N_2O emissions is possible (Clemens et al., 2002b). Schürer (2000) investigated the influence of the dilution of slurry (100 % slurry and 60 % slurry + 40 % water) on the emissions of NH_3, N_2O and CH_4. The measurements show that NH_3 and CH_4 are reduced within the first days whereas the N_2O emissions are increased.

Soil moisture contents will only be elevated in small parts of the soil volume, and diluted slurry will disperse more rapidly (Olesen et al., 1997). Therefore, the increased risk for denitrification and N_2O emission will be very transient. Also, the lower concentrations of metabolisable C and ammonium should limit microbial activity.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

2.9.12.2 Application of water after spreading

Details of measure:

A further option for increasing the infiltration rate is to wash slurry off grass and/or into the soil by applying water after spreading (see 2.9.12).

Advantages:

Application of water after spreading is connected with an increased rate of infiltration into the soil. Canadian results have shown that 6 mm of water can under some circumstances substantially reduce ammonia emissions compared to surface application alone.

Disadvantages:

Application of water after spreading is connected with higher energy (the application is an additional operation) and water expenses (a plentiful water is needed), a greater risk of surface run-off and N leaching.

In addition, higher soil water content has a strong influence on the process that leads to N_2O emissions (Davidson, 1992; Joergensen et al., 1998; Clemens & Huschka, 2001).

The additional operation increases soil compaction due to high loads and repeated run over after manure application.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↘	→

2.9.13 Manure additives / Acidification of manure

Details of measure:

The balance between ammonium-N and ammonia in solutions is dependent upon the pH. High pH favours loss of ammonia; low pH favours retention of ammonium-N. The percentage of NH_3 in solution at pH 6, 7, 8 and 9 is approximately 0.1, 1, 10 and 50, respectively. Thus, there is more potential for NH_3 volatilisation at higher pH. Molloy & Tunney (1983) found that NH_3 volatilisation effectively stopped at pH 5.0 for pig slurry and at pH 4.0 for cattle slurry. Acidification of slurry with acids (sulfuric, hydrochloric, nitric, phosphoric and lactic acid), base precipitating salts to control the pH (chloride and nitrate salts of magnesium and calcium are used mostly, although other soluble magnesium or calcium salts are also suitable). The addition of $CaSO_4$ or of organic additives influences the pH of the substrate (Vandré & Clemens, 1997) (see 1.5.3, 1.5.4).

Advantages:

Several researchers have observed reductions in pH and NH_3 volatilisation from livestock slurry or manure using base precipitating salts (Husted et al., 1991; Al-Kanani et al., 1992; O'Halloran & Sigrest, 1993; Vandré & Clemens, 1997). Lowering the pH of slurries to 4-5 by adding strong acids (e.g. $FeCl_3$, $Ca(NO_3)_2$ and super-phosphate) or salts (calcium and magnesium) decreases ammonia emissions by low and high rates respectively.

Results of Clemens et al. (2002a) show an increase of N_2O emissions after application but in total GHG emissions are greatly reduced. This is mainly caused by a decrease in NH_3 emissions.

Disadvantages:

There is considerable potential for increasing the rate of nitrification/denitrification and emissions of nitrous oxide due to the increase of the N_2O/N_2 ratio (Granli & Bockman, 1994).

$Ca(NO_3)_2$ additions enhance denitrification and lead to N_2O emissions (Vandré & Clemens, 1997).

Ca^{2+} additions decrease CO_2 volatilisation only at a high dose.

$CaCl_2$ effectively lowers slurry pH, but it is expensive and the additional Cl-load may have undesirable environmental effects.

Quantities required are too large to be practically feasible (environmental side effects after application).

Handling strong acids on farms is hazardous.

Chemical additives to reduce manure odours and gases have been popular with producers and vendors for many years. Unfortunately researchers have found it very difficult to prove the effectiveness of the many additives that are available. Of the products tested, relatively few have been shown to significantly reduce odour or gases. More investigations are needed to confirm the named positive mitigation effects.

And last but not least, it is difficult to justify acidification of slurry when acidification of agricultural soils must be counteracted with costly liming.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	↘	↘

2.9.14 Lime management

Details of measure:

Recent studies have suggested that increasing soil pH through liming could be an effective tool for reducing N_2O emissions, as at higher soil pH, N_2O is likely to be reduced to N_2 (Stevens & Laughlin, 1997; van der Weerden et al., 1999).

Advantages:

The N_2O emission factor of poorly and imperfectly drained soil is reduced by 15 % by increasing the pH of soils by 0.5 units.

Disadvantages:

However, the research data currently available are inconclusive and sometimes contradictory. Clearly, more work is required to accurately determine the impact of pH management on N_2O emissions.

High pH from liming may increase NH_3 emissions (see 2.9.13).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↑	→	→

2.10 Manure application techniques

A huge number of experiments have been carried out to quantify ammonia emissions after manure application and mitigation options. Research has mainly concentrated on slurry application, but a considerable number of experiments have also been carried out with farmyard manure.

CH_4 formation after field application seems not to take place so that CH_4 emissions are in the majority of cases neglected. Most of the strategies to reduce NH_3 rely on the balance of NH_3 and NH_4^+ and on the absorption of NH_4^+ negative charged surfaces. Up to 90 % of NH_4^+-N applied with slurry can be lost through NH_3 emissions (Horlacher & Marschner, 1990), substantially reducing the amount of plant-available N. Since the soil moisture has a big effect on N_2O emissions the field application of slurry under dry soil conditions may reduce the emissions. However, this may coincide with higher NH_3 emissions (Clemens & Huschka, 2001).

2.10.1 Slurry application techniques

Gaseous emissions from land application of slurries and solid manures account for a large proportion of the total ammonia emissions from agriculture. Controlling emissions from applications of manures to land is important, because land application is the last stage of manure handling. Without abatement at this stage, much of the benefit of abating during housing and storage may be lost. Furthermore, it is very important to minimise these losses at this stage because any ammonia saved during livestock housing or manure storage will be lost as nutrients for crop production if it is not controlled by appropriate field application techniques. Reducing ammonia losses from slurries and solid manures means more nitrogen is potentially available for grass and crop uptake.

Techniques include using machinery for decreasing the surface area of slurries and burying slurry or solid manures through incorporation into the soil (see 2.10.3). The effectiveness of these machines relies on reducing the surface area of slurry exposed to the air, increasing the rate of infiltration into the soil so that ammonium-N becomes bound to clay particles, or reducing air flow over the slurry surface by placement beneath a crop of grass canopy (Pain & Jarvis, 1999).

A number of factors must be taken into account to determine the applicability of each technique (UNECE, 1999). These factors include: soil type and condition (soil depth, stone content, wetness, travelling conditions), topography (slope, size of field, evenness of ground), manure type and composition (slurry or solid manure).

The reference for manure application techniques is defined as emissions from untreated slurry spread over the whole soil surface with a discharge nozzle and splash-plate ('broadcasting'). The slurry is forced under pressure through a nozzle, often onto an inclined plate to increase the sideways spread.

The NH_3 reduction efficiency is approx. 25 % for low efficiency techniques and approx. 60-90 % for high efficiency techniques, respectively. In general, changes in the way the manure

is applied to agricultural soils are not likely to affect emissions of CH_4 - according to study results from Sneath et al. (1997), Chadwick et al. (2000) and Wulf et al. (2001) CH_4 emissions after slurry application can be neglected.
Clemens et al. (1997), Velthof et al. (1997) and Weslien et al. (1998) found no significant differences between the application techniques.

2.10.1.1 Band spreading

Details of measure:

Band spreaders discharge slurry at or just above ground level through a series of hanging or trailing pipes. The width is typically 12 m with about 30 cm between bands. The technique is applicable to grass and arable land e.g. for applying slurry between rows of growing crops (UNECE, 1999).

Figure 18: Slurry application by band spreader.

Advantages:

A high ammonia and odour emission reduction on arable land and grassland has been reported by most of current studies. Pig slurry NH_3 emissions are significantly reduced whereas the emissions abatement potential for cattle manure is lower (UNECE, 1999; Döhler et al., 2002). The NH_3 mitigation effect increases if the slurry is applied on crops of higher size (>30 cm) or grassland (Döhler et al., 2002).
The distribution quality of band spreaders is very good with respect to the simple construction.
Moreover, the application with band spreaders lowers the contamination of forage.

Disadvantages:

Because of the width of the machine, the technique is not suitable for small, irregularly shaped fields or steeply sloping land. The hoses may also become clogged if the straw content of the slurry is too high (UNECE, 1999). Band spreaders are not usable on fields with high inclination.
This measure is lavish and costly.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↘

2.10.1.2 Trailing shoe

Details of measure:

This band spreading technique is mainly applicable to grassland. Grass leaves and stems are parted by trailing a narrow shoe or foot over the soil surface and slurry is placed in narrow bands on the soil surface at 20-30 cm spacings. The slurry bands should be covered by the grass canopy so the grass height should be a minimum of 8 cm (UNECE, 1999). The machines are available in a range of widths up to 8-12 m.

Figure 19: Trailing shoe slurry applicator (Source: Kishimoto, 2004; Chadwick & Laws, 2002).

Advantages:

A clear NH_3 reduction on arable land and grassland was reported by UNECE (1999). Döhler et al. (2002a) reported a different reduction of NH_3 emissions on grassland for cattle slurry and for pig slurry.

The distribution quality of a trailing shoe system is very good.

Application by trailing shoe causes an improved growth quality of crops and less crop contamination (low contamination of forage).

Disadvantages:

Applicability is limited by size, shape and slope of the field and by the presence of stones on the soil surface (UNECE, 1999). The system is not usable on fields with high inclination.

The trailing shoe system is lavish and costly (Eurich-Menden et al., 2004).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	→

2.10.1.3 Injection - open slot

Details of measure:

This technique is mainly for use on grassland. Different shaped knives or disc coulters are used to cut vertical slots in the soil up to 5-6 cm deep into which slurry is placed. Spacing between slots is typically 20-40 cm and working width 6 m. The application rate must be adjusted so that excessive amounts of slurry do not spill out of the open slots onto the surface (UNECE, 1999).

Figure 20: Injection manure applicator (Source: Iowa State University)

Advantages:

A substantial reduction of NH_3 emissions is feasible (UNECE, 1999). Döhler et al. (2002b) reported difference in NH_3 mitigation for pork and cattle slurry.

Disadvantages:

The technique is not applicable on very stony soil or on very shallow or compacted soils where it is impossible to achieve uniform penetration of the knives or disc coulters to the required working depth. Furthermore, injection can not be used in alpine regions or on long-term grassland.

The application by injection (open slot) causes higher energy use, higher expenses and sward damage.

This technique can lead to higher N_2O emissions from denitrification in comparison to broadcasting.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	→

2.10.1.4 Injection - closed slot

Details of measure:

This technique can be shallow (5-10 cm depth) or deep (15-20 cm). Slurry is fully covered after injection by closing the slots with press wheels or rollers fitted behind the injection tines. Shallow closed slot injection is more efficient than open slot in decreasing ammonia emission. To obtain this added benefit, soil type and conditions must allow effective closure of the slot. The technique is, therefore, less widely applicable than open slot injection. Tine spacing is typically 25-50 cm and working width 2-3 m.

Advantages:

A significant ammonia abatement efficiency is reported by UNECE (1999).

Disadvantages:

Although ammonia abatement efficiency is high, the applicability of the technique is severely limited. The use of deep injection is restricted mainly to arable land because mechanical damage may decrease herbage yields on grassland. Other limitations include soil depth and clay and stone content, slope and a high draught force requiring a large tractor. There is also a greater risk of nitrogen losses as nitrous oxide and nitrates, in some circumstances.
Injection causes higher fuel consumption and thus higher GHG emissions from fossil fuels.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	→

2.10.1.5 Pressurised injection

Details of measure:

In this technique, slurry is forced into the soil under a pressure of 5-8 bars and with a speed of 20-30 m s^{-1}.

Advantages:

Pressurised injection leads to a significant reduction in ammonia losses (Morken & Rorstad, 2002).

Disadvantages:

At present, the equipment for pressurised injection is not available on the market of most European countries (Döhler et al., 2002b). The use of this technical measure is connected with high expenses.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	→	↘

2.10.2 Solid manure application techniques

In general, different application systems of solid manure exist but no techniques have significant GHG mitigation potential. Therefore, there is no assessment included here. Reduction of GHG emissions is only possible if the solid manure is directly incorporated (see 2.10.3).

2.10.2.1 Rotaspreader

A side discharge spreader which features a cylindrical body and a pto-driven shaft fitted with flails running along the centre of the cylinders. As rotor spins, the flails throw the solid manure out to the side.

Figure 21: Rotaspreader (Source: Chambers et al., 2001).

2.10.2.2 Rear discharge spreader

A trailer body fitted with a moving floor or other mechanism which delivers solid manure to the rear of the spreader. The spreader mechanism can have either vertical or horizontal beaters, plus in some cases spinning discs.

Figure 22: Rear discharge spreader (Source: Chambers et al., 2001).

2.10.2.3 Dual purpose spreader

A side discharge spreader with an open top V-shaped body capable of handling both slurry and solid manure. A fast spinning impeller or rotor, usually at the front of the spreader, throws the material from the side of the machine. The rotor is fed with material by an auger or other mechanism fitted in the base of the spreader and a sliding gate controls the flow rate of the material onto the rotor.

Figure 23: Dual purpose spreader (Source: Chambers et al., 2001).

2.10.3 Incorporation of applied manure and/or slurry into soil

Details of measure:

Broadcast fertilisers can be incorporated, which increases root contact and plant growth, especially for the more immobile nutrients such as P and K. Incorporating of manure spread on the surface by ploughing is an efficient measure to decrease ammonia emissions. For this, the manure must be completely buried under the soil. Ploughing is mainly applicable to solid manures on arable soils. The technique may also be used for slurries where application (injection) techniques are not possible or not available. Similarly, it is applicable to grassland when changing to arable land (e.g. in a rotation) or when reseeding. Ammonia loss is rapid following spreading manures on the surface. Greater reductions in emissions are achieved when incorporation takes place immediately after spreading (incorporation of manure within 4-10 h after application). This requires that a second tractor is used for the incorporation machinery which must follow close behind the manure spreader. A more practical option might be incorporation within the same working day (24 h), but this is less efficient in reducing emissions.

Advantages:

UNECE (1999) reported a clear NH_3 reduction, but study results show that also a significant reduction of NH_3 emissions is possible. The reduction effect depends on the time frame between application and incorporation. At present, it is possible to use a field cultivator directly when applying the manure (Frick & Menzi, 1990).

The higher N efficiency can increase crop yields or may lower the need of mineral fertilisers, which reduces the total GHG emissions per product unit.

Incorporation reduces the surface run-off and thus the pollution of land, and ground and surface water.

Disadvantages:

N_2O can increase after slurry incorporation compared to broadcast application. But there may be an overestimation of the possible impact of those enhanced N_2O emissions (Chadwick et al., 1999; Wulf et al., 1999; Clemens & Ahlgrimm, 2001).

Incorporation will reduce the possibility of carbon sequestration (see 2.11).

Two separate field operations are due (e.g. in comparison to injection) so that this measure causes additional expenses (fossil fuel etc.).

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↑	→	↗

2.11 Carbon sequestration (enhancing soil carbon)

Details of measure:

Carbon sequestration in ecosystems occurs when C entering the system through gross primary production (photosynthesis) is greater than the C leaving the system through plant and heterotrophic respiration, lateral transfers, leaching and harvest. Measures to enhance carbon sequestration in agricultural soils are potential tools for mitigating global warming as well as enhancing soil protection. There is evidence that under current agricultural practices, many European soils are losing organic carbon and thus constitute sources of atmospheric CO_2 rather than sinks. This may be the case for arable cropping systems, which have tended towards greater specialisation and monoculture, and for farmed organic soils, such as peat lands. Farming practices additionally have an important impact on soil carbon content. Thus, there is a potential for carbon sequestration as well as for a reduction of GHG emissions from soils (Robertson et al., 2000).

Carbon sequestration in agricultural soils is accountable under Article 3.4 of the Kyoto Protocol which covers additional human-induced activities related to changes in GHG emissions and removals by sinks in agricultural soils and the land use change and forestry categories. The Bonn Agreement formulated at COP6bis in July 2001 clarifies the implementation of Article 3.4 as follows: In the context of agriculture, eligible activities comprise 'cropland management', 'grazing land management' and 'revegetation' provided that these activities have occurred since 1990, and are human-induced. The Marrakech Accord agreed at COP7 in November 2001 sets legally binding guidelines for reporting and accounting for agricultural carbon sinks. Thus, carbon sequestration in agricultural soils is a potentially suitable mechanism to ensure compliance with the EU's obligation to cut its GHG emissions.

Land use management provides a potential sink for CO_2, through building up soil organic matter stocks, which incorporate CO_2 taken from the atmosphere by plants. Agricultural carbon sequestration is based on the use of practices that can increase the amount of soil organic matter or humus which contains about 50 % carbon by mass. Historically, many soils used for agriculture have lost 20-40 % or more of their carbon through practices that led to low rates of C addition to soil (e.g. poor crop production, crop residue removal) and increased oxidation of soil organic matter. Practices that reverse this trend are adding more organic matter to soils and slowing its oxidation.

Options for increasing the role of agricultural land as a sink for CO_2 include carbon storage in managed soils and carbon sequestration e.g. reversion of surplus farmlands to natural ecosystems. A variety of practices that are increasingly being used, such as reduced and no-tillage can achieve these soil carbon gains. In addition, it is frequently the case that improvements in grasslands, such as reseeding with more productive species, fertiliser, irrigation and appropriate stocking rates, result in increased soil carbon.

Five to ten percent of the arable land has organic soils in northern Europe. Due to draining, the organic matter is mineralised to CO_2 and NH_4^+ (giving N_2O). In Sweden organic soils have been estimated to emit ca 10 % of the total anthropogenic emissions from all sectors (Kasimir Klemedtsson et al., 1997). Thus cultivation of organic soils is the opposite of C and N sequestration, having large CO_2 and N_2O emissions, the more drained and cultivated (root crops) the more emissions (see 1.3.6). A possibility to decrease the mineralisation is to increase the water level. A groundwater level just below the ground results in lower emissions of CO_2 and N_2O, while CH_4 emission is kept small. Permanent grassland prevents the breakdown of organic matter.

However, carbon storage in cropland and grazing land is considered in article 3.4 of the Kyoto Protocol and recent estimates suggest that the carbon mitigation potential on agricultural land in Europe is considerable (Smith et al., 2000). A calculation made by DG ENV assumed that 20 % of the surface of agricultural land in the EU could be used as a sink. According to Working Group 7 of the ECCP (European Climate Change Programme) this would result in an absorption potential of 7.8 Mt C, which correspond to 8.6 % of the total EU reduction objective. This is even more as estimated for forestry management measures in the EU (5.18 Mt C without afforestation). But carbon sequestration measures only work if they are maintained over decades.

Advantages:

The biological potential for carbon sequestration in agricultural soils through optimised land management could extend to 500 kg CO_2 ha^{-1} a^{-1} (100 Mt CO_2 equivalent a^{-1}). Practices that enhance soil C sequestration will improve the quality and fertility of soils as well as help to reduce erosion and soil compaction.

According to the estimates provided by the experts of ECCP, there is the potential to sequester up to 60-70 Mt CO_2 a^{-1} in the agricultural soils of the EU-15 during the first commitment period, which is equivalent to 1.5-1.7 % of the EU's anthropogenic CO_2 emissions.

Disadvantages:

Changes in carbon sequestration need to be considered over a longer time horizon since the effect is non-linear. Long-term experiments show that increases in soil carbon are often greatest soon after a land-use/land-management change is implemented. As the soil reaches a new equilibrium, the rate of change decreases, so that after 20-100 years a new equilibrium is reached and no further change takes place. This phenomenon is sometimes referred to as sink saturation. Whilst soil carbon levels may not reach a new equilibrium until 100 years after land-use/land-management change, the carbon sequestration potential may already be minimal after 20 years. Soil carbon sequestration does not, therefore, have limitless potential to offset CO_2 emissions; the yearly benefits will continue for about 20 years, but degressively.

Furthermore, soil carbon sequestered in arable soils may be non-permanent (Saggar et al., 2001). By reverting to old agricultural management or land-use practice, soil carbon is lost more rapidly than it accumulated. For soil carbon sequestration to occur, the land-use/land-management change must also be permanent. Whilst agricultural soils that are tilled every few years may contain more carbon than the same soils cultivated every year, much of the benefit of reduced tillage can be lost by ploughing, when compared to a permanent management change. For practical purposes, therefore, in order to implement a meaningful carbon sequestration policy on agricultural land, management changes must be permanent.

In general, the actual rate of carbon sequestration is highly uncertain. A greater research effort to study, monitor and quantify management of carbon sequestration is a practical option for managing GHG emissions.

The main problem of including agricultural soil carbon stock changes in the inventories of net GHG emissions is that of verifiability. The soil carbon pools are large and the changes are slow. However, even small changes in soil carbon pools may contribute significantly to national GHG emissions; such small relative changes in soil carbon pools are very difficult to determine from soil sampling (Olesen & Petersen, 2002).

Moreover, it has to be considered that C is not sequestered alone, but together with other nutrients such as N. Humus is composed of C and N. To be able to sequester C, there is a cost of N. The sequestered N is a future risk of N_2O emission, since the N content of the soil is one of the driving variables for N_2O emission (Smith et al., 2000).

Finally, some measures are connected with an additional use of herbicides due to less soil cultivation.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.11.1 Improve residue management (higher crop residue return)

Details of measure:

A better use of animal manure, crop residues, cover crops, farmyard manure, compost and sewage sludge, by applying the available material on cropland, instead of on grassland or elsewhere as is common practice, is recommended.

Advantages:

The ECCP 'working group on sinks related to agricultural soils' indicate the clear sequestration potential of this measure.

Chemical fertiliser can be partly replaced, leading to reduced N_2O emissions and reduced nitrate leaching. Accounting of additional nitrogen input is required to avoid nitrogen overdose and nitrate losses. Higher residue return reduces erosion.

This measure is easy to implement and has a positive long-term impact on farm income due to better soil fertility. On-farm composting can provide an additional source of income (capital and operational costs incurred by setting up a composting facility at farm level may be offset by 1) a fee for taking organic waste 2) income from selling compost 3) savings in fertiliser, water consumption, disease suppression.).

Disadvantages:

Residue management has the potential to increase costs due to transport (depends on the distance), purchase of organic material and compost production. The widespread production of compostable waste limits the distance between production and application sites of compost in most cases as well as transportation costs.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	↗

2.11.2 Land use change

Details of measure:

Land use change is defined as a permanent revegetation of arable (set-aside) land (e.g. afforestation) or extensivation of arable production by introduction of perennial components. One common case is the land use change (abandonment) of marginal cropland reseeded to permanent grassland or surplus-cropland seeded to permanent grassland. The conversion of arable land to grassland includes the possibility to expand field margins, on which grass should be grown, and possibly shrubs or trees.

Advantages:

The ECCP 'working group on sinks related to agricultural soils' indicate a significant sequestration potential of this measure.

Disadvantages:

Change to more grassland is connected with more animals causing more manure, which can again increase GHG emissions. In any case, when considering any land management change, the likely effect on other, non-CO_2 greenhouse gases needs to be considered.

The implementation of this measure and the impact on the farm income is regionally specific and only positive if linked to compensation payment for nature protection.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	→

2.11.3 Reduced tillage and no-tillage

Details of measure:

Zero tillage systems represent an extreme form of cropland management in which any form of mechanical soil disturbance is continuously abandoned except for shallow opening of the soil for seeding, like continuous mulch-seed or direct drill. In reduced tillage systems soil disturbance is kept at a minimum or reduced compared to conventional ploughed systems.

Reduced tillage systems involve reducing the number of passes with tillage equipment and managing the residues from the previous crop. These systems leave residue cover on the soil surface. Reduced tillage or no-tillage (zero tillage) is the likely cause of C sequestration in the no-till system (Paul et al., 1997; Robertson et al., 2000).

Advantages:

In no-till systems there is minimal disturbance by planting equipment. Depending on the crop most of the soil surface is covered throughout the year. Smith et al. (2000) suggest that when these potential increases of N_2O production are converted to carbon equivalents and included in the calculation, the total mitigation effect in terms of the GWP is significantly reduced compared to when only soil carbon sequestration is considered.
The ECCP 'working group on sinks related to agricultural soils' indicate a substantial sequestration potential for this measure.
Less fossil fuel is used which can reduce the energy input up to 50 %.
In some regions reduced or no-tillage represents a suitable instrument for erosion control and soil conservation.

Disadvantages:

Reduced tillage includes a wide range of different practices, depending on various climate and soil conditions. The sequestration rate as well as the potential environmental and socio-economic impacts can thus (according to a few studies) only be estimated qualitatively, in comparison to zero tillage.
The implementation is connected with high initial machinery costs and probably with a more intensive machine usage and an additional pesticide usage due to less soil cultivation. Difficulties may occur in cultivation of heavy clay soils, without autumn ploughing and/or freezing of soil.
N_2O emissions may increase, as soils may become more anaerobic and advance denitrification under no-till. For example, recent studies have shown that as much as one half of the mitigation effect attributed to carbon sequestration under zero tillage can be reversed by an increase in N_2O emissions (Smith et al., 2001).
Soil structure improves under most conditions, but increased bulk density may lead to reduced rootability and infiltration in some cases.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.11.4 Promotion of permanently shallow water table in farmed peat land

Details of measure:

To promote a permanently shallow water table in farmed peat land (see 1.3.6, 2.2).

Advantages:

The ECCP 'working group on sinks related to agricultural soils' indicate a significant sequestration potential of this measure.
This measure has benefits for wildlife, biodiversity, landscape and water retention as well as reducing N_2O emissions.

Disadvantages:

The implementation of this measure and the impact on the farm income is regionally specific. In addition, this measure is only cost-effective for the farmer if the needed structural engineering measures to conserve a permanently shallow water table in the farmed peat land are compensated by payments for nature protection.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	→

2.11.5 Reduced bare fallow frequency / Elimination of bare fallow

Details of measure:

Based on cropping Rasmussen et al. (1998) concluded that loss of soil organic matter is related to excessive oxidation and absence of C input during fallow. Adapting crop rotations and crop/farming systems with avoidance of bare fallow (e.g. by permanent revegetation of set-aside areas with perennial grasses or woody bioenergy crops instead of rotational fallow) would be an option to increase carbon inputs to the soil (see 2.11.6).

Advantages:

Doran et al. (1998) concluded from long-term studies that decline of soil organic matter could be slowed by a more intensive cropping system. Recent study results show that the elimination of bare fallow has for temperate climate a similar carbon sequestration potential to afforestation.
Elimination of bare fallow makes the soil more susceptible to erosion that leads to the depletion of soil carbon and nitrate leaching.

Disadvantages:

Bare fallow periods are not inevitable for all crop rotations.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	→

2.11.6 Cultivation of energy crops

Details of measure:

Biofuel production with e.g. short-rotation coppice plantations or perennial grasses (see 2.11.2 and 2.12) have considerable potential for reducing emissions (e.g. Smith et al., 2000) due to both fuel substitution and the introduction of a perennial crop with potential gains in soil carbon sequestration (see 2.12.3). Only the carbon sequestration effect is considered here, which is much smaller than the beneficial effect resulting from fossil fuel replacement. In annual bioenergy plants (e.g. rape seed for biodiesel, sugar beet for bioethanol) carbon sequestration in the soil is not enhanced.

Advantages:

The ECCP 'working group on sinks related to agricultural soils' indicate a high sequestration potential of this measure whereas the benefit from substitution of fossil fuels by bioenergy is much greater than the effect from carbon sequestration.

Disadvantages:

The impact of this measure on the farm income is regionally specific and only positive if linked to subsidies or emerging markets.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.12 Bioenergy crop production

Details of measure:

Bioenergy crops can be used in two ways: 1) as a solid fuel being combusted alone or in a co-combustion process with coal or, 2) after conversion processes, as a source of gaseous or liquid fuel. Bioenergy by biofuels, combustion or digestion of energy crops etc. has among other measures the greatest potential for using agricultural land to mitigate greenhouse gas emissions because they can sequester soil carbon (see 2.11.6) and substitute fossil fuels. The short- and long-term environmental and social implications of large-scale biomass production relate to the energy balance expressed as fossil fuel input for the production, conversion and use of biomass, effects on soil resources, quality and quantity of water resources, poor resilience of monocultural plantations and the impacts for biodiversity, sustainability and amenity (IPCC, 2000).

Large-scale biofuel plantations resemble intensive agricultural schemes and often inherit adverse environmental impacts on natural resources including soil, water and biodiversity. The energy balance in the production, use and transportation of biofuels tends to be more efficient in large scale enterprises with an input-output ratio of currently 1:10 to 1:15 and potentials up to 1:30. Comparatively low conversion factors impose a particular barrier for small-scale projects. However, newly developed conversion technologies (e.g. anaerobic digestion) can also be run efficiently in small-scale enterprises with the likelihood of environmental social benefits if designed according to specific project circumstances (IPCC, 2000).

Advantages:

Shifting from traditional to modern biofuels often include social and environmental benefits such as increased employment, higher productivity of land, reduced urban and agricultural waste and improved nutrient recycling. Given their carbon neutrality biofuels are also increasingly discussed in the context of their contribution to the mitigation of fossil fuel based greenhouse gas emissions. Bioenergy production by anaerobic digestion of manure (and/or co-substrates) and production of biomass for energy reduce GHG emission by substituting fossil energy use. In addition, production of biomass for energy may reduce nitrous oxide emissions and increase carbon storage in soils (Olesen, 2002).

Disadvantages:

Considering an increasing world population and corresponding food demand the use of arable land for bioenergy crop production could lead to ethical problems.

Sequestration of soil C is reversed if land use is changed to cultivated crops. Thus, sequestration may be of short duration (see 2.11).

Large-scale industrial biofuel plantations are known for adverse impacts on biodiversity. Good plantation design for biofuel and timber production would include set-aside areas for native flora and fauna and regulate management limits for riverbanks and erosion-prone slopes etc.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	→

2.12.1 Combustion of energy crops

Details of measure:

The simplest, cheapest and most common method of obtaining energy from biomass is direct combustion. Any organic material with a water content low enough to allow for sustained combustion can be burned to produce energy. Solid fuel can be combusted alone or in a co-combustion process with coal. The heat of combustion can be used to provide space or process heat, hot water or, through the use of a steam turbine, electricity.

Advantages:

This measure can mitigate GHG emissions from fossil fuels. The carbon substitution by replacing fossil carbon by renewable carbon is not to be mixed up with carbon sequestration since the carbon is rapidly burnt to substitute fossil fuels.

Disadvantages:

Energy crops provide an inhomogeneous material for the combustion process what could result in ineffective combustion and emissions. Additionally, there are combustion residues at the end of the process.

There are ethical problems to burn comestible goods (acceptance problems of producers and "consumers").

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

2.12.2 Biofuel production

Details of measure:

In general, almost all biomass products can be converted into commercial fuels which can substitute fossil fuels. These can be used for transportation, heating or electricity generation. The conversion is accomplished through the use of several distinct processes. These processes include both biochemical and thermal conversions to produce gaseous, liquid and solid fuels that have high-energy content, are easily transportable, and therefore are suitable for use as commercial fuels.

Wood and many other similar types of biomass that contain lignin and cellulose (miscanthus etc.) can be converted through thermochemical processes into solid, liquid or gaseous fuels. Pyrolysis is still the most common thermochemical conversion of biomass to commercial fuel. During pyrolysis, biomass is heated in the absence of air and breaks down into a complex mixture of liquids, gases, and a residual char. If wood is used as the feedstock, the residual char is what is commonly known as charcoal. With more modern technologies, pyrolysis can be carried out under a variety of conditions to capture all the components, and to maximise the output of the desired product be it char, liquid or gas.

Biochemical conversion of biomass is completed through alcoholic fermentation to produce liquid fuels and anaerobic digestion, resulting in biogas. Alcoholic fermentation of crops such as sugarcane, sugar beets and maize to produce ethanol for use in internal combustion engines has been practiced for years e.g. in Brazil, France and Sweden where ethanol has been blended with gasoline for use in automobiles. With slight engine modifications, automobiles can operate on ethanol alone.

Anaerobic digestion of biomass (see 1.6) has been practiced for almost a century, and is very popular in many developing countries such as China and India. The organic fraction of almost any form of biomass, including sewage sludge, animal wastes and industrial effluents, can be broken down through anaerobic digestion into methane and carbon dioxide. This biogas is a reasonably clean burning fuel which can be captured and put to many different end uses such as cooking, heating or electrical generation.

Advantages:

Biofuels, the substitute for fossil fuels made from renewable sources, have considerable potential for reducing emissions due to both fuel substitution and the introduction of a perennial crop with potential gains in soil carbon sequestration.

The IPCC report on 'Land Use, Land-Use Change and Forestry' concludes: "From a policy perspective, the potential for biofuel displacement of fossil fuel is an order of magnitude greater than any other land-use change. It may also impact atmospheric carbon levels earlier and at a lower cost than any other sector measure."

Disadvantages:

Competition situation if set-aside subsidies cease to exist.

There are ethical problems related to burning comestible goods (acceptance problems of producers and "consumers").

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

2.12.2.1 Co-digestion of energy crops

Details of measure:

Co-digestion is the simultaneous digestion of a homogenous mixture of two or more substrates. In Germany 95 % of modern biogas plants use co-substrates (Weiland et al, 2004). Cattle slurry is for 75 % of the biogas plants the basic substrate and pig slurry for 25 %. About 70 % of biogas plants use maize silage and approx. 50 % grass silage as co-substrate. Most of farmers use 3-4 different co-substrates. More than 30 % of farmers use more than 7 different co-substrates (Weiland et al., 2004).

Due to higher methane production factors (B_o-factors; Table 4) of co-digestates in comparison to manure an additional biogas collection is possible.

Advantages:

The addition of energy crops or silage as a co-substrate allows for further increase in the biogas productivity of agricultural digesters. Energy crops can be grown on fallow land as a new income for farmers. The biomass can be fed directly, or after ensilage, as a co-substrate

Table 4: Methane production factors (B_o-factors) for manure and organic matter for methane production during biogas digestion (Weiske et al., 2004).

Substrate	B_o [m^3 CH_4 kg^{-1} VS]
Manure from heifers (6-25 months)	0.182
Manure from cows	0.204
Clover-grass silage / red clover	0.288
Maize silage	0.45
Triticale whole crop silage	0.291
Potatoes	0.359
Grains	0.358
Straw	0.24
Alfalfa	0.289
Pea / Field bean	0.399

to digesters. However, the overall economics of energy crops co-digestion depends crucially on crop yield, raw material production costs, achievable energy prices, biogas yields and on the energy utilisation degree.

Co-digestion can provide an improved nutrient balance and the additional co-digestate will also increase the fertiliser amount.

Disadvantages:

There are ethical problems related to using comestible goods (acceptance problems of producers and "consumers").

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	→	↗

2.12.3 Carbon sequestration by biomass production

Details of measure:

The link to climate change mitigation is based on its carbon neutrality and potential for additional carbon sequestration (see 2.11.6). The sustainable use of biomass for energy production, that is the use of biomass at a rate at which it can be reproduced on the same land, is per se carbon neutral. Carbon neutrality implies that the carbon, which is released to the atmosphere through the combustion process, is sequestered equally in the re-growing biomass. Most biomass production schemes will, however, sequester additional carbon in a so-called buffer stock, which allows for continuous biomass production and its storage.

The growth of all plants is based on the absorption of carbon dioxide from the atmosphere. Carbon content in dry biomass is about 50 % (weight). The CO_2 is released back into the atmosphere during the decay or combustion of biomass.

The sequestration of carbon, which is the underlying process of biomass production through land use, land use change and forestry activities, is by itself an eligible mitigation option for GHG emissions under the Kyoto Protocol. Developing countries have the opportunity to contribute to energy and carbon sequestration related mitigation activities under the Clean Development Mechanism (CDM) of the Kyoto Protocol.

Article 3 of the Kyoto Protocol has recognised that anthropogenic activities in the land use, land use change and forestry sector could affect the emissions of GHGs from sources and removals by sinks. Article 3.3 describes activities such as afforestation, reforestation and deforestation that are accounted for as GHG sources or sinks. But Article 3.4 additionally mentions that the Parties may decide to account for additional activities aiming for carbon sequestration in "agricultural soils and the land-use change and forestry categories". Such additional activities include the management of crop-, grass-, and wetlands and also forest management.

Advantages:

The ECCP 'working group on sinks related to agricultural soils' indicate a high sequestration potential of this measure whereas the benefit from substitution of fossil fuels by bioenergy is much greater than the effect from carbon sequestration.

Disadvantages:

The impact of this measure on the farm income is regionally specific and only positive if linked to subsidies or emerging markets

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

3 Management-based measures

The agricultural sector is characterised by large regional differences in both management practices and the rate at which it would be possible to implement mitigation measures. Comprehensive management measures in agricultural systems are needed at regional and global levels to evaluate changes in emissions and mitigation requirements (Freney, 1997). Management measures imply, however, changes in farming which directly affect agricultural yields (e.g. animal density) and require in most cases new investment.

In general, farmers have no incentive to adopt GHG mitigation techniques unless they improve profitability. Some abatement technologies, such as reduced or no-till agriculture (see 2.11.3) or strategic fertiliser placement and timing (see 2.9.10 and 2.9.11), are already being adopted for reasons other than concern for climate change. Options for reducing emissions, such as improved farm management and increased efficiency of nitrogen fertiliser use, still have high potential to maintain or increase agricultural production with positive environmental effects such as GHG mitigation. These management options may directly cause GHG mitigation or indirectly by an increase of productivity or reduced input of e.g. mineral fertiliser.

3.1 Integration of plant and animal production

Details of measure:

The trade of feed results in movement of N from one region to another, concentrating the N in the receiving region (see 1.4.1). Therefore, the integration of plant and animal production makes it possible to grow the feed needed on the farm, optimising and closing the nutrient cycle.

Advantages:

If feed production is close to animal production, the manure can be used as a source for nutrients, decreasing the need for fertiliser addition, reducing the amounts of nutrient cycling in the agro-ecosystem. This may reduce N_2O and NH_3 emissions, lower nitrate leaching and CH_4 emissions from enteric fermentation on regional level.

Less transportation and need for fuels will also reduce GHG emissions and costs.

Disadvantages:

In many regions of Europe farms are already specialised in either specific livestock or arable farming. All changes would require a large reorganisation of the European agriculture.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

3.2 Extensification / Intensification and livestock density

Details of measure:

Both intensification and extensification of agricultural practices is taking place throughout Europe. For a good description of extensification or intensification processes data needs range over several categories: population, land, outputs, inputs, and land capitalisation (Table 5).

Intensification is characterised by a change in production practices on a given area to either increase intensity of production or increase the yield of crop and/or animal production whereas for extensification (on e.g. marginal land) the productivity per defined area can be significantly lower. Both are defined by the intensity ratio of input (fertiliser, concentrates) and output (meat, milk etc.) and thus for most of the farms by the livestock density.

Advantages/Disadvantages:

According to several studies it is undoubtedly that extensification compared to intensification reduces the GHG emissions per animal or defined area. Crutzen et al. (1986) suggest a lower average annual emission value of 35 kg CH_4 per animal for cattle under extensive management compared to 55 kg CH_4 per animal under intensive management. This is also the case for extensive and intensive systems for sheep (5-8 kg CH_4 per animal) and swine (1-1.5 kg CH_4 per animal). This less intensive production has various positive environmental side-effects such as wildlife benefits, animal welfare benefits, improved soil structure etc.

In contrast to extensification, it is significant that the higher yielding intensified production systems only emit moderate levels of greenhouse gases with relatively low emissions per production unit (kg of wheat, meat, milk). Martin & Seeland (1999) reported that high milk production per cow gives a lower CH_4 emission per litre of milk produced (conversely small cows on a poor diet give high CH_4 emissions per litre of milk produced). Therefore, intensification of farming improves the viability of holdings and the maintenance of employment. However, the combination of increasing specialisation and intensification leads to higher environmental and other risks as well as a reduction in diversity.

The most cost-effective reductions are those that intensify production per animal and make more extensive use of land. For example, on dairy farms, this would mean smaller numbers of higher yielding dairy cows, eating more high-energy feed such as those based on cereals, and grazing land to which less nitrogen is applied. As with many modelling studies, the absolute levels of the results - in this case, the emissions associated with different farm practices - are very uncertain, due to the underlying uncertainties in the models.

In general, the choice for one of these options is affected by the price of land so that there may be increases in intensification in some areas whilst land price changes may encourage extensification in others.

Table 5: Categories that define extensification or intensification.

Population	Land	Inputs	Outputs	Land capitalisation
• Population density • % of agricultural in total labour force • % of part-time farmers • % of regional income derived from agriculture • Age of farm household/agricultural population • Gender and education of farm managers	• % natural and semi-natural areas in region • % cultivated land in total land • % of fallow land in total cultivated land • % of irrigated in total cultivated land • % of mechanised cultivated land in total cultivated land • % of set-aside crop land in total cultivated land • % of abandoned agricultural land • Multi-cropping index • Livestock density • % of animals permanently kept in stables • Settlement patterns • Sediment loss (erosion indicators)	• Total value of inputs per unit of land/animal • Fertiliser use (chemical, organic) • Use of agro-chemicals • Use of irrigation water • Feed use (% concentrates, primary products, residues and by-products) • Machinery use • Energy use • Use of plastic sheets (% of cultivated area covered) • Tillage methods • Efficiency of nutrient application	• Crop yields • Total crop production • Crop distribution and rotation • Livestock yields • Livestock production • Livestock types • Gross value of output per unit of agricultural land • % of marketed output	• Farm structure (size, fragmentation) • Machinery (size, power, replacement interval) • Irrigation infrastructure/ equipment

The evaluation provided assumes that the same agricultural production level is needed and that no compensation for extensification is paid:

Extensification:

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↘	↑	↗	↘

Intensification:

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	↘	↗

3.3 Increase of grazing in comparison to animal housing

Details of measure:

Recent studies indicate that the increasingly stringent and costly, but highly uncertain, requirements for compliance with environmental regulations are causing many dairy operators to rethink the wisdom of their move to confinement production technology.

There are increasing numbers of reports of dairy operators changing to grazing-based production systems (see 1.3.1). Research showed that for a typical dairy farm a grazing-based operation produced higher average annual net returns than a confinement system.

Urine excreted by grazing often infiltrates into the soil before substantial NH_3 emissions can occur. Because of the relatively low losses from grazing compared with losses from the housed phase, one suggestion has been to extend the grazing season so that the amount of excreta produced indoors is reduced (Pain & Jarvis, 1999).

Advantages:

Several studies reported that NH_3 emissions per animal are lower for grazing animals than for those in housing where the excreta are collected, stored and applied to land (Pain & Jarvis, 1999).

Additionally, cost advantages of 10-15 % are estimated by Waßmuth (2002). Waßmuth (2002) also appraises that the extension of grazing will result in an increase in animal welfare and health as well as a reduced amount of ectoparasites and respiratory diseases.

A higher share of grazing will also lead to more landscape conservation.

Disadvantages:

Grazing animals contribute slightly more than 10 % to the global N_2O budget (Oenema et al., 1997). Emissions are partly caused by the fact, that the distribution of N returns via grazing animals are more heterogeneous than if applied as manure, and more exposed to leaching losses because of extremely high point levels. In this regard, patches are important sites for N loss via NH_3 volatilisation (Jarvis et al., 1989), via nitrate leaching (Ryden et al., 1984) and via denitrification and N_2O emissions (Ryden et al., 1986). According to Oenema et al. (1997) grazing animals affect the emission of N_2O in three ways, by 1) return of N in urine patches, 2) return of N in dung patches, and 3) treading and trampling. Also Velthof et al. (1998) argue that grazing-derived emissions are sometimes larger than N fertiliser-derived emissions.

Mosier et al. (1998) reported that N_2O emissions from livestock are much higher when animals are in meadows than when they are in animal housing systems. Therefore, N_2O emissions from animal waste management can be reduced by restricting grazing (Velthof et al., 1998). This will result in a shift from high N_2O emissions during grazing to lower emissions from anaerobic waste management systems. When grazing is restricted, the cattle will be stalled for a longer time and more urine and dung will be collected and stored as slurry. Here, various technical measures are available to control and reduce emissions (see 1.1, 1.5, 1.6 etc.). The slurry will then be applied as fertiliser to grassland (by the use of improved application techniques, see 2.10) and, consequently, less N fertiliser will be required. Consequently, the N_2O emissions are larger for dung and urine patches in grassland than for slurry which has been properly applied to soil. Therefore, total leaching-derived and N fertiliser-derived N_2O emissions will also be lower when grazing is restricted. Thus, restricted grazing may rather be an option to mitigate N_2O emissions from intensively managed grasslands than an extension of grazing.

But generally, the emission reduction achieved by increasing the proportion of the year spent grazing will depend on the reference system, the time animals are grazed, the fertiliser level of the pasture etc. However, other effects should also be taken into account when switched to restricted grazing; this system requires larger slurry storage tanks and sophisticated slurry application equipment.

Finally, the potential for increasing grazing is often limited by soil type, topography, farm size and structure (distances), climatic conditions etc.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↘	↗	↗	↘

3.4 Increase of the grassland ratio in relation to arable land

Details of measure:

Increasing the grassland ratio in relation to arable land covers several advantages of the above described technical and/or management-based GHG mitigation measures: 1.3.1, 'Extension of grazing in comparison to animal housing', 2.11 'Carbon sequestration (enhancing soil carbon)', 2.11.2 'Land use change' and 3.3 'Increasing of grazing in comparison to animal housing'.

Advantages:

If the grassland ratio rises carbon sequestration can be increased.
Especially good for organic soils, but may also reduce GHG from mineral soils.

Disadvantages:

The agricultural productivity on arable land can be higher in comparison to grassland. Moreover, the flexibility of production on arable land is higher.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	↗	→

3.5 Transport of manure to areas with deficit

Details of measure:

In certain regions with specialised e.g. pig and poultry farms the regional production of N, P and K in manure can exceed the regional needs and threshold values. Manure can be transported in such cases to areas with deficit.

Advantages:

The use of manure on regional level has the advantage that surplus produced manure of one farm can be used at another farm to reduce additional mineral fertiliser requirements. The improved use of manure and fertiliser will reduce N_2O emissions and N leaching.

Disadvantages:

Additional transport would increase GHG emissions from fossil fuels and costs, especially when manure with low dry matter content is transported.
The exchange of manure increases hygiene hazards. Thus, in some countries such an exchange of manure is not allowed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

3.6 Anaerobic digestion

This also management-based technical measure is discussed in detail in section 1.6.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	↗	↗

4 Reduction of use of fossil fuels

Many common activities in agriculture use energy from fossil fuels - from running machinery like tractors and ploughs, to lighting buildings, and operating milking or other equipment in barns. And using fossil fuels, of course, is directly related to the release of greenhouse gas emissions.

4.1 Increase in energy efficiency / Reduction of energy use

Details of measure:

Agriculture is an energy-intensive industry. Energy is used for prechain products (machinery, fertiliser etc.), crop production, transportation and livestock housing. Energy savings will not only reduce costs but will also reduce GHG emissions.
There are different options how to reduce energy use or to improve the energy efficiency:

- insulating the walls and floors,
- controlling rodents to reduce damage to installed insulation,
- switching to energy-efficient lighting and equipment (e.g., fan motors),
- installing heat recovery and exchange systems,
- automating energy use with energy controllers (e.g., thermostats), timers or sensors,
- using solar energy techniques for water and space heating,
- match equipment size to operation,
- inflate tires properly,
- minimise weight and ballast,
- use natural grain drying procedures,
- use continuous flow-bin or conventional column dryers,
- reduce transportation,
- reduce field operations (e.g. by reduced tillage / no-tillage) (see 4.1.3),
- reduce use of fertiliser (e.g. by use of N_2-fixing crops) (see 4.1.1),
- reduce use of pesticides (see 4.1.1),

Advantages:

Although some of these listed measures to reduce the use of energy or increase the energy efficiency will result in marginal savings this will in total considerably reduce both costs and GHG emissions from fossil fuels.

Disadvantages:

Some of the listed measures will need additional investment costs or are not applicable to all farms.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	→

4.1.1 Reduced use of energy-intensive products / Energy-efficient production

Details of measure:

For the supply of different prechain products, which are important for the agricultural production, high amounts of energy are needed. In Table 6, the GHG emissions for the supply of, for instance, fertilisers and pesticides representative for the conditions in Germany (energy mix, transportation distances etc.) are presented (Patyk & Reinhardt, 1997; Kaltschmitt & Reinhardt, 1997). If the use of these energy-intensive products such as N fertiliser is reduced, a substantial amount of energy can be saved. If furthermore the prechain production is optimised by new technologies, this would additionally increase the energy efficiency of the whole agricultural production.

Table 6: GHG emissions for the supply of fertilisers and pesticides (active ingredient) in Germany (Patyk & Reinhardt, 1997; Kaltschmitt & Reinhardt, 1997).

Fertiliser	**Relation**	**Emissions [g kg^{-1} fertiliser or active ingredient] (related to P, K and Ca)**				
		CO_2	**CH_4**	**N_2O**	**NH_3**	**NO_X**
N	1 kg N	2829	7.45	15.1	6.69	15.8
P	1 kg P_2O_5	1117 (2558)	2.07 (4.74)	0.04 (0.09)	0.0120 (0.0275)	8.58 (19.65)
K	1 kg K_2O	617 (746.6)	1.38 (1.67)	0.05 (0.061)	0.0019 (0.002)	1.15 (1.39)
CaO	1 kg CaO	112 (156.8)	0.171 (0.239)	0.0002 (0.0003)	0.0002 (0.0003)	0.52 (0.73)
Active ingredient	1 kg active ingredient	4921	0.18	1.50	0.16	6.92

Advantages:

New technologies promise higher production efficiencies e.g. conversion from fossil fuels, production of fertilisers etc. If this increased energy efficiency will reduce the energy use per product unit of the prechains, this would substantially reduce the indirect GHG emissions of the total agricultural sector. If moreover the individual farmer will reduce the use of the respective product, this would have high potential to reduce the GHG emissions of the whole farm or per agricultural product unit.

Disadvantages:

Farmers have no influence on the development of new production technologies of prechain products such as fertilisers.

Less use of products like fertilisers can reduce the productivity which would increase the GHG emissions per product unit.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

4.1.2 Energy-efficient building design

Details of measure:

Traditional farm buildings were not generally designed to be energy efficient. However, more modern facilities offer better temperature and air quality control, through updated heating and ventilation systems - and in some cases, air conditioning (see 1.2.2). Energy-efficient building design that takes advantage of passive solar heating techniques also reduces energy use by minimising the demand for energy right from the start. But one of the most efficient ways to save energy is to build naturally ventilated houses (this is especially feasible in cattle husbandry; see 1.2.2.1).

At the same time, a number of measures can make older farm buildings more energy efficient. Such measures include:

- try to arrange design to maximise east-west orientation
- maximise southern exposure
- choose a rectangular building design with a very long axis
- use shade in the design and landscaping
- use energy-efficient lighting and appliances
- use fluorescent lighting
- use management controls for lighting
- conduct energy audit for home, barns and other heated areas
- use energy-efficient outer wall designs
- use recommended R-values for wall and ceiling insulation
- use natural light whenever possible
- use energy efficient windows and doors in heated areas
- use energy-efficient heat sources
- use interlocked heating and ventilation system
- ventilate to reduce moisture and to protect insulation
- use building code for proper overhang
- use high-efficiency water heater
- supplement heat wood furnace and alternative energy uses
- acquire access to energy-efficient emergency power sources
- use vapour barriers to reduce moisture (condensation) in wall insulation
- insulate foundations
- follow maintenance schedules for machinery and equipment
- follow recommended preventive maintenance procedures
- do not leave equipment running unnecessarily

Advantages:

In total all these listed measures will considerably reduce both costs and GHG emissions from fossil fuels - although some of these measures to reduce the use of energy or increase the energy efficiency will result only in marginal savings.

Disadvantages:

Most of the listed measures will need investment cost or are not applicable to all farms.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	→	→	↗

4.1.3 Reduced tillage or no-tillage

Details of measure:

Sowing a crop without prior cultivation and with very little soil disturbance at seeding (reduced and no-till or zero-till, direct drilling etc.) reduces additional operations such as ploughing (see 2.4). This conserves energy for crop production (Retzlaff, 1980).

Advantages:

No-till crop production conserves fossil fuel energy in addition to conserving soil.

Disadvantages:

This measure is connected with high initial machinery cost and associated with increased pesticide usage and its negative environmental side effects.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	↗	↗	↗

4.1.4 Precision farming

Details of measure:

The goal of precision farming is to gather and analyse information about the variability of soil and crop conditions in order to map precise fertiliser and pesticide requirements and so to maximise the efficiency of crop inputs within small areas of the farm field (see 2.5). To meet this efficiency goal the variability within the field must be controllable. Efficiency in the use of crop inputs means that fewer crop inputs such as fertiliser and chemicals will be used and placed where needed. The benefits from this efficiency will be both economical and environmental.

Advantages:

Precision farming aims to minimise losses and enhance fertiliser use efficiency as well as pesticide efficiency, which reduces GHG emissions from prechains and crop production.

Disadvantages:

The precision farming techniques are only financially feasible for bigger farms or contractors (in the case of contractors also applicable for smaller farms).
Sufficient know-how of the farmer is needed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↗	↗	→	↗

4.2 Energy recycling e.g. through biogas production from manure

Details of measure:

Systems utilising energy produced from biomass are typical examples of energy recycling systems. Biotechnology is one of the future-oriented technologies, and one that will play a major role in the exploitation of biomass energy. The recycling of residues, manure or wastes by e.g. anaerobic digestion to minimise the additional production of fertilisers and additionally to use the produced heat and power of generation is a complex concept to reduce GHG emission of a whole farm.

Advantages:

On farm level or in relation to the different product units, the energy recovery of un- or partly-used organic materials represents an option with high direct GHG mitigation potential due to less mineral fertiliser use. Moreover, the use of residues, waste etc. as co-substrates and the subsequent targeted use as manure according to the demand of plants would additionally reduce N losses by N_2O emissions in fall and winter.

Disadvantages:

Additional investment costs for an energy recycling system are needed.

GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
↑	→	↗	↗

5 Political instruments

Policy recognises that many initiatives in sustainable agriculture to address production inefficiencies or environmental management simultaneously provide other net benefits such as mitigation of greenhouse gases. Therefore, the adoption of agricultural management strategies such as minimum tillage, precision farming, controlled traffic, sustainable grazing systems or improved climatic awareness all can be undertaken for sustainability reasons and provide greenhouse benefits. There are different measures how policy can influence GHG mitigation (taxes, subsidies etc.). The main ideas behind political instruments are demonstrated in the following chapters.

5.1 More non methane meat production

To consume more meat from monogastric animals (non-ruminant) such as pigs and poultry instead of meat from ruminant animals such as cattle and sheep.

5.2 Restriction of stocking rate

Restriction of stocking rate or manure quota in relation to defined agricultural area.

5.3 Restriction of grazing

Restriction of grazing (Velthof et al., 1998), which may reduce N_2O emissions (Velthof et al., 1998).

However, when grazing is restricted, the cattle will be in the stable for a longer time and more manure will be collected and stored. Therefore, this option will increase both NH_3 and CH_4 emissions

5.4 Top limits on application and regulated times of application

Limitation on the timing of manure and fertiliser application (e.g. nitrogen per ha applications - sub-optimal fertiliser-N application)

- in dependence of soil conditions, type and slope, climatic conditions, rainfall, land use and agricultural practices (crop rotation systems), and
- to be based on a tight balance between the nitrogen requirements of the crops and the nitrogen supply to the crops.

In 1999, the EU Nitrate Directive already limited the application of animal manure to a maximum amount of N applied to the land of 170 kg ha^{-1} a^{-1}. The rationale behind the nitrogen application limit is to reduce the total amount of nitrogen in the system by replacing inorganic nitrogen fertiliser with organic nitrogen from manure. Most nitrogen pollution (nitrate leaching, NH_3, N_2O emissions) is lost from the surplus nitrogen in the system, i.e. that which is not taken up by the crop. In addition, fertilisation and manure application is not allowed in several European countries during the freezing period of soil, to prohibit losses from leaching and runoff.

For top limits and regulated times of manure application additional storage capacity for manure can sometimes be needed (Hendriks et al., 1998 assume a 20 % increase in manure storage capacity), which is connected with higher costs. Furthermore, longer manure storage times will cause an increase in emissions associated with manure storage.

5.5 Fertiliser-free zones

Defined zones or areas adjacent to surface of water (ditch, stream, river) or other valuable habitats to prevent runoff.

5.6 Taxes and quota on N fertiliser

Taxation or N quotas to limit the rates of inorganic fertiliser (N) application, in order to discourage unnecessary use where a system is already in surplus.

Fertiliser taxes are already in use in some EU15 countries (e.g. Denmark, Sweden).

There is some doubt that taxes and quota on N fertiliser are an effective instrument for reducing nitrogen over-application, as farmers will continue to pay higher prices for the same amount of fertiliser as a risk aversion response. Vatn et al. (1996) reported that taxes do not motivate farmers to modify nitrogen fertiliser practices or adopt a better use of manure unless the taxation level is very high. Their results suggest a 50 % tax rate is required for a 5 % reduction in nitrogen per ha applied on grain crops, and a 20 % reduction in N ha^{-1} on grass. A tax rate of 100 % could induce a 10 % reduction in nitrogen per ha applied on grain crops, and a 40 % reduction in N ha^{-1} on grass. Other authors come to similar conclusions.

5.7 Subsidising the reduction of methane

According to COM (2000) the minimum value of a ton of methane reduction is 21 times the minimum price of 20 € per ton of CO_2 equivalent (= 420 € per ton of CH_4). Methane emissions of 100 kg per cow and 100 cows per farm may result in 10 tonnes of CH_4 per farm on average (420 € per farm with an estimated reduction of 10 %). It is questionable whether this reduction or cost provides an incentive for a farmer to change the production method or invest in biogas plants.

Other areas of interest might be:

- a subsidy for high fat concentrates,
- a subsidy for high NSC concentrates,
- a subsidy for high malate grass seeds (if such varieties exist or can be bred),
- an extra premium for early slaughtered beef animals.

5.8 Taxation of feed imports

Taxation on feed imports to reduce the significant transfer of nutrients from the already nutrient deficient developing world to the nutrient surplus areas of the industrialised world. (Such taxation might be supplemented with, or used as, subsidies for a transfer of nutrients back to the developing world).

This measure is not difficult to establish. The introduction of market pricing for inputs such as feed would promote the conservation and use of local products as it would reduce unfair advantages of imported products of developing countries.

This measure is politically difficult to achieve.

5.9 Incentives for the geographical distribution of crop and livestock activities

One possibility: Especially N_2O production is a function of weather, where a wet and warm climate gives higher emissions than a dry and cool climate. Animal production in the later areas would therefore be preferable.

5.10 Area payments

5.10.1 Nitrate vulnerable zones

Area payments for less application of fertiliser and manure in nitrate vulnerable zones (NVZs): Nitrate vulnerable zones are designated areas in which the over-application of nitrogen to crops can have major implications on levels in groundwater and therefore posing a potential health risk. The implementation of NVZs were considered to reduce N use and leaching by 5 %.

5.10.2 Provision of direct subsidies for marginal land

Payments (direct subsidies) for the production of marginal land.

5.11 Reduced price support for product

Vatn et al. (1996) predict that a 33 % price reduction would result in a 5 % reduction in nitrogen application to grain crops, and 20 % reduction to grass.

However, removal of price support would also mean that farming in some marginal areas would no longer be viable. Meester (1994) estimated that about 40 % of land in EU12 would be too marginal to continue to compete with more productive areas, under a scenario of technological improvements and the removal of the social support aspects of the CAP.

5.12 Subsidisation of production and use of bioenergy

Subsidisation of the production and use of bioenergy. Use of biofuels diminishes fossil fuel combustion thereby also reducing net GHG emissions.

However, subsidies can make agricultural biofuel production economically feasible.

6 Summary

		GHG mitigation potential	Technical feasibility	Environmental added value	Cost effectiveness
1	**Measures related to livestock and poultry farming**				
1.1	Animal breeding and husbandry				
1.1.1	Livestock breeding	↑	↗	→	↗
1.1.2	Artificial insemination	↑	→	→	↗
1.1.3	Planned selection of male/female at insemination (embryo and sperm sexing)	↗	↘	→	↗
1.1.4	Twinning	↗	↘	→	→
1.1.5	Lifetime efficiency (calves, cattle, cows / meat, milk)	↗	↘	→	→
1.1.6	Multi use of cows (milk, calves and meat)	↗	↗	→	→
1.2	Animal housing and in-barn manure management				
1.2.1	New low-emission livestock and poultry housing systems	↑	→	→	↗
1.2.2	Ventilation				
1.2.2.1	Natural ventilation	↑	↗	→	↑
1.2.2.2	Ventilation rate	↗	→	→	↗
1.2.2.3	Decreasing of air velocity above manure	↗	→	→	↗
1.2.3	Reducing the temperature of the manure and surfaces it covers	↗	↘	→	↘
1.2.4	Purification of animal house emissions (filtration technologies)				
1.2.5	Tied systems instead of loose-housing systems	↑	↗	→	↗
1.2.6	Cages and aviaries instead of floor systems for layer hens	↑	↗	→	↗
1.2.7	Reduction of manure contaminated surface areas	↗	→	→	↗
1.2.8	Keeping surfaces, manure and animals dry				
1.2.8.1	Improved drinking systems	↗	↗	→	↗
1.2.8.2	Drying of manure	↑	↗	→	↗
1.2.8.3	Keeping animals clean and dry	↗	↑	→	↑
1.2.9	Absorption of urine / Use of bedding material	↗	↗	→	↗
1.2.9.1	Straw-based systems	↗	↗	→	↗
1.2.9.2	Deep litter systems	→	↗	→	↗
1.2.10	Slurry-based systems / Deep dung channels	→	↘	→	↘
1.2.11	Rapid separation of faeces and urine	↗	↗	→	→
1.2.12	Partly or fully slatted floors	↗	↗	→	↗
1.2.13	Frequent manure removal	↑	↗	→	↑
1.3	Grassland and grazing management				
1.3.1	Extension of grazing in comparison to animal housing	↘	↗	↗	↘
1.3.2	Adaptation of fertilisation on demand	↑	↑	↗	↑
1.3.3	Consideration of pasture age and composition	↗	↗	→	↗
1.3.4	High sugar grasses	↗	↗	→	↗
1.3.5	Increase of N fixation	↑	↗	↗	↑
1.3.6	Groundwater level adjustments for grassland (e.g. by drainage)	→	↘	→	↘
1.3.7	Conversion of arable land to grasslands	↗	↗	↗	↗
1.3.8	Cattle winter management	↗	→	→	↗
1.4	Feeding strategies				
1.4.1	Optimised plant and animal production	↗	→	→	↗
1.4.2	Analysis of forage and fodder	↗	↗	→	↗
1.4.3	Improve forage quality	↗	↗	→	↗
1.4.4	Reduction of feed imports / More feed production on farm scale or local level	→	→	↘	→
1.4.5	Mechanical treatment of feed	↗	→	→	→
1.4.6	Chemical treatment of low quality feedstuffs	↗	→	→	→

1.4.7	Optimisation of livestock feeding / Adjusting livestock feed composition				
1.4.7.1	Low nitrogen feed	↗	→	→	→
1.4.7.2	Minimising protein over-consumption / Increase of amino acids	↗	→	→	↗
1.4.7.3	Replacing roughage by concentrates	↗	↗	→	→
1.4.7.3.1	Including more non-structural carbohydrates in concentrates	↗	↗	→	→
1.4.7.4	High fat diet	↗	↗	→	↗
1.4.7.5	(Multi)Phase feeding	↑	↗	→	↑
1.4.7.6	Increasing rumen efficiency:				
1.4.7.6.1	Hexose partitioning	↗	↗	→	→
1.4.7.6.2	Propionate precursors	↗	↗	→	↗
1.4.7.6.3	Directly fed microbes (acetogens, methane oxidisers)	↗	↗	→	→
1.4.7.6.4	Genetic engineering/modification	↑	→	→	?
1.4.7.6.5	Immunisation / Immunogenic approach	↑	↗	→	→
1.4.7.6.6	Defaunation (alteration of bacterial flora)	↗	↘	→	↘
1.4.8	Increasing animal productivity through the use of additives				
1.4.8.1	Oils / Fats	↗	→	→	↗
1.4.8.2	Probiotics	→	↗	→	→
1.4.8.3	Enzymes	↑	↗	→	↗
1.4.8.4	Antibiotics	↗	↗	→	↗
1.4.8.4.1	Ionophores	↑	↗	→	↘
1.4.8.5	Halogenated compounds	↗	→	→	?
1.4.8.6	Hormones				
1.4.8.6.1	Steroids	↗	↗	↘	↗
1.4.8.6.2	Growth hormones - Bovine somatotropin	↗	↗	→	↗
1.5	Outdoor manure management (storage techniques)				
1.5.1	Decreasing or eliminating the airflow across slurry and FYM	↗	↘	→	↘
1.5.2	Reducing the temperature of manure	↗	↘	→	↘
1.5.3	Reducing the pH of manure	↗	→	→	↘
1.5.4	Manure additives	↗	↗	→	↘
1.5.5	Reducing the surface per unit volume of slurry or FYM stores	↑	↗	↗	↗
1.5.6	Mechanical separation of solids of manure	↗	↗	→	→
1.5.7	Composting of solid manure or slurry with added solids or of FYM	↗	→	↗	↗
1.5.8	Controlled denitrification processes in slurry	↗	↗	→	↘
1.5.9	Controlled aeration during slurry storage	→	↗	→	↘
1.5.10	Minimising of stirring	↗	↑	→	↑
1.5.11	Fill-pipe into manure storages underneath the slurry surface	↗	↗	→	↗
1.5.12	FYM storage techniques				
1.5.12.1	Increase of straw amounts	↗	↗	→	↗
1.5.12.2	Compaction of FYM	↗	↗	→	→
1.5.12.3	Flexible cover	↗	↘	→	↗
1.5.12.4	Comminution of FYM	↗	↘	→	→
1.5.12.5	Repeated turnover of FYM	↗	→	↗	↗
1.5.13	Slurry storage techniques				
1.5.13.1	Consideration of the filling level	↗	↗	→	→
1.5.13.2	Tanks instead of lagoons	↗	→	↗	↗
1.5.13.3	Natural crust	↗	↑	→	↑
1.5.13.4	Cover techniques				
1.5.13.4.1	Low technology covering				
1.5.13.4.1.1	Straw, peat and bark	↗	↗	→	↗
1.5.13.4.1.2	Granulates	↗	↗	→	↗
1.5.13.4.1.3	Floating oil	↗	↗	→	↗
1.5.13.4.2	Flexible plastic cover	↑	↗	→	↗
1.5.13.4.3	Rigid covers and roofs	↑	→	↗	↗
1.6	Anaerobic digestion	↑	→	↗	↗
1.6.1	Storage of digested slurry	↑	→	→	↗
1.6.2	Application of digested slurry	→	→	↗	→
1.6.3	Main factors affecting the efficiency of anaerobic digestion				

1.6.3.1	Digestion and/or co-digestion				
1.6.3.2	Anaerobic digestion in cooler and warmer countries				
1.6.3.3	Farm scale or centralised digestion plants				
1.6.3.4	Use of power / power & heat / power & heat & cooling				
2	**Measures on crop production**				
2.1	Continuous plant cover (catch crops and intercrops)	↗	↗	↗	↗
2.2	Optimisation of water management (irrigation, drainage)	→	↘	→	↘
2.3	Prevention of soil compaction	↗	↗	↗	↗
2.4	Reduced tillage or no-tillage	↑	↗	↗	↗
2.5	Precision farming	↗	↗	→	↗
2.6	Changing from winter to spring cultivars	→	→	↘	→
2.7	Breed cultivars that improve N use efficiency	↗	→	→	↗
2.8	Use of N fixing crops	↑	↗	↗	↑
2.9	Slurry, manure and fertiliser management				
2.9.1	Soil analysis	↗	↗	→	↗
2.9.2	Manure analysis	↗	↗	↗	↗
2.9.3	Adaptation of fertilisation and pesticide application on demand	↑	↑	↗	↑
2.9.4	Matching the type of fertiliser to seasonal conditions	↗	↗	→	↗
2.9.5	Optimisation of split application schemes	↗	→	↘	↗
2.9.6	Consideration of fertiliser types	↗	↗	→	↗
2.9.7	Slow and controlled release fertilisers and fertilisers with nitrification or urease inhibitors				
2.9.7.1	Slow and controlled-release fertilisers	↑	↗	↗	↗
2.9.7.2	Nitrification and urease inhibitors	↑	↗	↗	↗
2.9.8	Substituting inorganic by organic nitrogen fertiliser	→	↗	→	↘
2.9.9	Application of digested slurry	→	→	↗	→
2.9.10	Timing of application	↑	↗	→	↑
2.9.11	Fertiliser placement (band placement)	↗	↗	→	↗
2.9.12	Increasing rate of infiltration into soil				
2.9.12.1	Dilution of manure	↗	↗	→	→
2.9.12.2	Application of water after spreading	↗	↗	↘	→
2.9.13	Manure additives / Acidification of manure	↗	→	↘	↘
2.9.14	Lime management	↗	↑	→	→
2.10	Manure application techniques				
2.10.1	Slurry application techniques				
2.10.1.1	Band spreading	↗	↗	→	↘
2.10.1.2	Trailing shoe	↑	↗	→	→
2.10.1.3	Injection - open slot	↑	↗	→	→
2.10.1.4	Injection - closed slot	↑	↗	→	→
2.10.1.5	Pressurised injection	↑	→	→	↘
2.10.2	Solid manure application techniques				
2.10.2.1	Rotaspreader				
2.10.2.2	Rear discharge spreader				
2.10.2.3	Dual purpose spreader				
2.10.3	Incorporation of applied manure and/or slurry into soil	↑	↑	→	↗
2.11	Carbon sequestration (enhancing soil carbon)	↑	↗	↗	↗
2.11.1	Improve residue management (higher crop residue return)	↗	↗	↗	↗
2.11.2	Land use change	↑	↗	↗	→
2.11.3	Reduced tillage and no-tillage	↑	↗	↗	↗
2.11.4	Promotion of permanently shallow water table in farmed peat land	↑	↗	↗	→
2.11.5	Reduced bare fallow frequency / Elimination of bare fallow	↑	↗	↗	→
2.11.6	Cultivation of energy crops	↑	↗	↗	↗
2.12	Bioenergy crop production	↑	↗	→	→
2.12.1	Combustion of energy crops	↑	↗	↗	↗
2.12.2	Biofuel production	↑	↗	→	↗
2.12.2.1	Co-digestion of energy crops	↑	↗	→	↗
2.12.3	Carbon sequestration by biomass production	↑	↗	↗	↗

3	**Management-based measures**				
3.1	Integration of plant and animal production	↗	→	→	↗
3.2	Extensification / Intensification and livestock density				
	Extensification	↘	↑	↗	↘
	Intensification	↗	→	↘	↗
3.3	Increase of grazing in comparison to animal housing	↘	↗	↗	↘
3.4	Increase of the grassland ratio in relation to arable land	↗	↗	↗	↘
3.5	Transport of manure to areas with deficit	↗	↗	→	→
3.6	Anaerobic digestion	↑	→	↗	↗
4	**Reduction of use of fossil fuels**				
4.1	Increase in energy efficiency / Reduction of energy use	↗	↗	→	↗
4.1.1	Reduced use of energy-intensive products / Energy-efficient production	↗	→	→	↗
4.1.2	Energy-efficient building design	↗	→	→	↗
4.1.3	Reduced tillage or no-tillage	↑	↗	↗	↗
4.1.4	Precision farming	↗	↗	→	↗
4.2	Energy recycling e.g. through biogas production from manure	↑	→	↗	↗
5	**Political instruments**				
5.1	More non methane meat production				
5.2	Restriction of stocking rate				
5.3	Restriction of grazing				
5.4	Top limits on application and regulated times of application				
5.5	Fertiliser-free zones				
5.6	Taxes and quota on N fertiliser				
5.7	Subsidising the reduction of methane				
5.8	Taxation of feed imports				
5.9	Incentives for the geographical distribution of crop and livestock activities				
5.10	Area payments				
5.10.1	Nitrate vulnerable zones				
5.10.2	Provision of direct subsidies for marginal land				
5.11	Reduced price support for product				
5.12	Subsidisation of production and use of bioenergy				

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