Wageningen UR Livestock Research

Partner in livestock innovations

Report 488

Measures to reduce ammonia emissions from livestock manures; now, soon and later

June 2011

LIVESTOCK RESEARCH
WAGENINGEN UR

Colophon

Publisher
Wageningen UR Livestock Research
P.O. Box 65, 8200 AB Lelystad
Telephone +31 320 - 238238
Fax +31 320 - 238050
E-mail info.livestockresearch@wur.nl
Internet http://www.livestockresearch.wur.nl

Editing
Communication Services

Abstract
Various possible options to further decrease ammonia emissions from livestock manure were explored in a desk study. Techniques and their impact on the processes leading to NH_3 production and volatilization are described. Research priorities are identified.

Keywords
Ammonia emission, housing, pasture, manure application, abatement options

Reference
ISSN 1570 - 8616

Authors
C.M. Groenestein
M.C.J. Smits
J.F.M. Huijsmans
O. Oenema

Title
Measures to reduce ammonia emissions from livestock manures; now, soon and later

Report 488

Report 488

Measures to reduce ammonia emissions from livestock manures; now, soon and later

C.M. Groenestein
M.C.J. Smits
J.F.M. Huijsmans
O. Oenema

June 2011

Preface

In dit rapport worden diverse opties verkend om de ammoniakemissie uit de landbouw verder te verminderen. Dit op verzoek van het Ministerie van Economische Zaken, Landbouw en Innovatie. Een verdere vermindering van ammoniakemissies uit de Nederlandse veehouderij is wenselijk om het ammoniakplafond voor 2020 volgens de NEC richtlijn te behalen. In dit rapport worden ook ontwikkelingen geschetst die de omvang en verdere structuur van veehouderijsectoren tussen 2010 en 2020 kunnen beïnvloeden en daarbij de ammoniakemissie. Het ontwikkelen en toepassen van additionele emissie reducerende maatregelen zal daardoor de komende jaren wellicht nog belangrijker worden. Deze inventarisatie vond in 2009 en 2010 plaats. Daarom kan het voorkomen dat technieken die in dit rapport als veelbelovend zijn gekenmerkt al erkende technieken zijn.

De auteurs

Samenvatting

Het doel van deze studie is “het verkennen van diverse mogelijke opties om de ammoniakemissie uit de landbouw verder te verminderen”. De nadruk ligt op de NH_3 emissies uit dierlijke mest van de grondgebonden en intensieve veehouderij.
Sinds begin jaren negentig zijn al veel maatregelen geïmplementeerd om de ammoniakemissie uit de Nederlandse landbouw te beperken. Deze maatregelen waren zodanig succesvol dat de NH_3 emissie al met ca 50% is afgenomen ten opzichte van de tweede helft van de jaren 80 van de 20^e eeuw. De emissiereductiedoelstellingen van de NEC richtlijn voor 2010 zijn min of meer bereikt, maar verdere reducties na 2010 zijn vereist. Tegen die achtergrond heeft het Ministerie van Economische Zaken, Landbouw en Innovatie gevraagd om de mogelijkheden voor verdere reductie te verkennen.

De mogelijke ontwikkelingen in de Nederlandse veehouderij gedurende het volgende decennium (2010-2020) worden beschreven en scenario’s met lagere NH_3 emissies geschetst. De veranderingen in het beslissingsdomein van de veehouders door veranderingen in markten, technologieën en overheidsbeleid worden bediscussieerd. Er kunnen veranderingen optreden in de structuur van de veehouderijsector en de plaats op de wereld waar dierlijke productie plaatsvindt. Dergelijke veranderingen kunnen de ammoniakemissie beïnvloeden en daarmee ook de behoefte aan reductiemaatregelen om de natuur in de wijdere omgeving te beschermen door deze minder te belasten met ammoniak uit dierlijke mest. Uit de resultaten kan afgeleid worden dat zorgvuldig gekozen pakketten van technische maatregelen effectiever zijn in het verlagen van de emissies en tegen lagere kosten dan volumemaatregelen (zoals minder dieren, minder N excretie). Dit in het bijzonder voor de emissies van ammoniak en fijnstof (PM_{10}). Een afname van de dierlijke stikstof- (en fosfor-) excretie kan echter wel additionele synergie effecten hebben

De processen die leiden tot vorming en vervluchtiging van NH_3 worden ook in dit rapport beschreven. Reducties van NH_3 emissies kunnen worden bewerkstelligd door de verschillende processtappen te beïnvloeden. De maatregelen waarop gefocust moet worden om de emissie te reduceren zijn:

- verlaging van de concentratie van ureum/urinezuur;
- remmen van de omzetting van ureum/urinezuur naar NH_4^+;
- remmen van de omzetting van NH_4^+ naar NH_3;
- verlaging van de concentratie van NH_4^+ en NH_3;
- beperken van de uitwisseling van ammoniak tussen urine/mest en lucht;
- het wassen van NH_3 uit de lucht.

Afhankelijk van de focus, zullen maatregelen de NH_3 productie en vervluchtiging beïnvloeden in de hele mestketen (stal, opslag en toediening) of slechts in een deel van die keten.

Ammoniakemissie reducerende maatregelen die al genomen zijn, worden in dit rapport op een rij gezet; gevolgd door maatregelen die in de pijplijn zitten (R&D) en perspectiefrijke maatregelen voor de toekomst. Vanwege het risico van afwenteling, zijn ook de mogelijke impacts ingeschat van maatregelen op de emissies van de broeikasgassen lachgas en methaan en fijn stof en geur. Impacts op diergezondheid, dierwelzijn, werkomstandigheden en energieverbruik worden vermeld voor zover er zicht is op een groot (neven-) effect. Deze mogelijke afwentelingseffecten en andere neveneffecten worden in deze studie meegenomen in het kader van de integrale duurzaamheid (‘People, Planet, Profit’).

Er is een aanzet gemaakt om de meest perspectiefrijke maatregelen te selecteren om het emissieplafond voor 2020 van de NEC richtlijn te bereiken. Daartoe zijn drie criteria gehanteerd: de potentiële impact op ammoniakemissie; de toepasbaarheid in verschillende diercategorieën en het huidige stadium van onderzoek. Maatregelen die in meerdere diercategorieën toepasbaar zijn, kunnen als extra aantrekkelijk aangemerkt worden. In de rundveesector is de urgentie om te komen tot nieuwe toepasbare maatregelen het hoogst omdat daar tot nu toe weinig emissiereducerende maatregelen geïmplementeerd zijn. Dit beperkt bedrijven in hun ontwikkeling of maakt de verdere ontwikkeling onmogelijk, zoals in en nabij NATURA 2000 gebieden. Bij de selectie van maatregelen kunnen ook ontwikkelingen die in dit rapport beschreven zijn, meegewogen worden, ook al zijn die ontwikkelingen niet allemaal primair gericht op emissiereductie.

Op basis van bovenstaande criteria wordt aanbevolen om de volgende maatregelen prioriteit te geven in het onderzoek:

- ureaseremmers; toe te passen op vloeren en in ingestrooide ruimtes die bevuild worden met mest en urine, in de mestkelder en optioneel nog een dosering ureaseremmers direct voordat de mest wordt toegediend;
- toepassing van luchtwassers in de stal (interne luchtwassers) en toepassing van luchtwassers op de lucht die afzonderlijk uit de kelder kan worden afgezogen met of zonder het volledig verwijderen (strippen) van de ammoniak uit de mest;
- het beperken van de ventilatiebehoefte door verbetering van de stal (bv. isolatie, geconditioneerde lucht) en verbetering van ventilatiesystemen;
- het combineren van gereduceerde ventilatiebehoefte met luchtwassers, zodat de luchtwassers minder capaciteit hoeven te hebben en daardoor lagere investeringskosten en operationele kosten;
- toepassing in varkensstallen van roostervloeren met flexibele flappen in de roosterspleten;
- topprestatie gerichte zodenbemesting of mest onderwerken (met minimale emissies en maximale benutting van nutriënten).

Additioneel wordt aanbevolen om de mogelijkheden en kwantitatieve impact te bestuderen van het lokaal reduceren van de depositie van ammoniak in gevoelige natuurgebieden zoals Natura 2000 door het implementeren van maatregelen op veehouderijbedrijven nabij deze natuurgebieden.

Summary

The purpose of the study reported here was "to explore various possible options to further decrease NH3 emissions from agriculture". The emphasis is on NH3 emissions from livestock manures. Starting from the early 1990s, a large number of measures have already been implemented to decrease NH3 emissions from agriculture in the Netherlands. These measures have been rather successful and have decreased NH3 emissions by about 50% relative to the emissions during the second half of the 1980s. The emission reduction targets of the NEC Directive for 2010 have been achieved more or less, but further reductions are requested. That is the reason why the Ministry of Economic Affairs, Agriculture and Innovation, The Netherlands requested to explore options for further decreases.

The possible developments in Dutch livestock production during the next decade are described and scenario's with lower NH_3 emissions are reviewed. The changes in the decision environment of farmers due to changes of markets, technology, and policy are discussed. Thereby, the structure and location of animal production systems may change. Such changes can have effect on NH_3 emissions, and thereby also on the need of abatement measures to protect the wider environment from manure NH_3. The results suggest that carefully chosen packages of technological measures are more effective in decreasing emissions and at lower costs than volume measures (less animals, less N excretion), especially the emissions of NH_3 and PM_{10}. However, a decrease in animal N (and P) excretion may have additional synergistic effects.

The processes leading to NH_3 production and volatilization are described. Reduction of NH_3 emissions can be realized by influencing the different pathways in the process of NH_3 volatilization. The focus of measures to be taken to reduce emissions are presented: concentration of urea/uric acid; production of NH_4^+ from urea/uric acid; conversion of NH_4^+ to NH_3; concentration of NH_4^+ and NH_3; exchange of NH_3 between manure and air; scrubbing NH_3 from air. Depending on focus, measures affect NH_3 production and volatilization in the whole manure chain: housing, storage and application, or just in a part of the chain.

Measures are listed that have already been taken to reduce NH3 emission, the ones at present in research, and best possible measures for the future. Because of the risk of pollution swapping, other emissions are explored as well: the greenhouse gases nitrous oxide and methane, particulate matter and odour. To reconcile the economic and social values of the optimal sustainable triangle of the three P's People, Planet Profit, animal health, animal welfare, working conditions and energy use are addressed when relevant.

An approach is provided to accomplish the best possible way to reach the emission ceiling for 2020 of the NEC Directive. Therefore three general criteria were taken into account: the potential impact on ammonia emission; the applicability in different animal categories; the present stage of research. Also is considered that measures that are applicable in more than one animal category are worthwhile but in cattle the sense of urgency is highest because little progress in implementing low emission systems has yet been made on commercial dairy cattle farms and this may restrict these farms in their development considering the Natura 2000. Finally, developments as described earlier in this report are taken into account, even though not primarily aimed at reducing emissions.

Given the above, it is recommended to study the following measures with priority:

- urease inhibitors application on floors and in litter, in the slurry pit and optionally another inhibitor dose just before slurry application,
- internal air scrubbing and pit air scrubbing with or without stripping ammonia;
- reducing ventilation requirements by improving animal houses (e.g. insulation, air conditioning) and ventilation systems;
- combining reduced ventilation requirements with air scrubbing;
- slatted floors with flexible flaps in pig houses;
- high performance shallow injection or manure incorporation.

Additionally it is recommended to study the possibilities and quantitative impact of locally reducing the deposition of ammonia in vulnerable nature area's like Natura 2000 areas by implementing farm measures at close distances of these nature areas.

Table of contents

1 Introduction

Agriculture is the main source of atmospheric ammonia (NH_3), with a share of ~80% in the global emissions of NH_3 into the atmosphere (Bouman *et al.*, 1997). The emissions originate mainly from livestock manures and urea and ammonium-based fertilizers. Emissions of NH_3 to air create various unwanted ecological effects and human health effects (e.g. Galloway *et al.*, 2008). In response, series of governmental policy measures have been implemented in a number of OECD countries and especially the European Union (EU) to decrease these emissions. Important policy documents include the 1999 Gothenborg Protocol, the 2001 EU National Emission Ceiling Directive (NEC Directive 2001/81/EC) and the EU Integrated Pollution Prevention and Control Directive (IPPC Directive 2008/1/EC), which are all under revision now (in 2010). In view of the objectives of these policy measures and in particular the emission ceiling (target) for 2020 of the NEC Directive, the Ministry of Economic Affairs, Agriculture and Innovation, The Netherlands wants to explore further possibilities and perspectives for reducing ammonia emission from agriculture in cost-effective ways.

Starting from the early 1990s, a large number of measures have already been implemented to decrease NH_3 emissions from agriculture in the Netherlands. These measures have been rather successful and have decreased NH_3 emissions by about 50% relative to the emissions during the second half of the 1980s (e.g. De Haan *et al*., 2009). The emission reduction targets of the NEC Directive for 2010 have been achieved, but further reductions are requested. That is the reason why the Ministry of Economic Affairs, Agriculture and Innovation of The Netherlands requested to explore options for further decreases. This is especially challenging, as basically all 'low-hanging fruit' has been picked already during the last two decades. The study was executed on the basis of desk studies and 'brainstorm meetings'.

The purpose of the study reported here was "to explore various possible options to further decrease NH_3 emissions from agriculture". The emphasis is on NH_3 emissions from livestock manures. Emissions from fertilizers are relatively small, because carbonated ammonium nitrate (CAN; $CaCO_3$ + NH_4NO_3) is the dominated nitrogen fertilizer and NH_3 emissions from these fertilizers are relatively small (Bussink, 1996, Velthof *et al*., 2009). Throughout this report, 'manure' and 'manures' are used in generic terms, i.e., including all types of livestock excrements and slurries.

Chapter 2 describes the possible developments in Dutch livestock production during the next decade and reviews scenario's with lower NH_3 emissions. Sources of NH_3 emissions are floors and manure storages in housing and outside storages, manure application and pasture. In the Netherlands emission from outside storages are already low because of obligatory covering. Therefore, reducing NH_3 emissions from outside storages is not considered in this report. Chapter 3 describes the processes leading to NH_3 production and volatilization and Chapter 4 gives the measures already taken to reduce NH_3 emission, the ones at present in research, and, based on the inventory in Chapter 2 and 3, best possible measures for the future. Because of the risk of pollution swapping, other emissions are explored as well. To reconcile the economic and social values of the optimal sustainable triangle of the three P's People, Planet Profit, animal health, animal welfare, working conditions and energy use were addressed. Chapter 5 provides an approach to accomplish the best possible way to reach the emission ceiling for 2020 of the NEC Directive.

2 Possible developments in agriculture during the next decades

This chapter discusses the changes in the decision environment of farmers due to changes of markets, technology, and policy. Thereby, the structure and location of animal production systems may change. Such changes can have effect on NH_3 emissions, and thereby also on the need of abatement measures to protect the wider environment from manure NH_3.

2.1 Transitions in global livestock production

Livestock production systems in the world are in transition because of developments and changes in demand for food, technology, markets, transport and logistics. This transition leads to drastic changes in livestock production systems it selves as well as in its institutional organization and geographical locations. Increasingly, livestock products become ‘global commodities’, and livestock production systems are producing in an ‘open, competitive, global market. These developments are facilitated by the increasing demand for animal products because of the increasing urban population and the increasing consumption of animal products per capita, although there are large regional and continental differences. The demand for livestock products concentrates in urban centers. With high rates of consumption, rapid growth rates and a shift towards animal-derived foods, urban centers increasingly drive the sector. The retail, processing industry and suppliers of animal feed and technology dictate the sector, while the livestock producers (farmers) become increasingly dependent on the organization within the whole food chain, and have less influence (FAO, 2009; Steinfeld *et al*., 2010).

A major aspect of the transition is the organization and regional positioning of production chains in order to minimize production and delivery costs. For a given technological context, production costs vary with input costs. Animal feed is the major input to livestock production, followed by labour, energy, water and services. Input costs vary substantially from place to place within countries as well as across continents. Access to technology and know-how is also unevenly distributed, as is the ability to respond to changing environments and to market shocks. There are also institutional and cultural patterns that further affect production costs, access to technologies and transaction costs. The combination of these factors shapes the economic landscape within which commodity chains become distributed in the world to minimize their overall cost, in a context of cheap and safe transportation. As a consequence, livestock production systems become larger, specialized and more intensive in most areas of the world. Global livestock production is expected to increase by up to 50% during the next three to four decades, due to the increase in demand for animal products by the growing human populations. The demand for animal products will increase especially in SE Asia and Latin America, and to a lesser extent in Africa. Increases in animal production in Europe and Northern America are expected to be relatively small. (FAO, 2009; Steinfeld *et al*., 2010).

Civic society pressure groups and political parties put also pressure on the intensification and up-scaling of the livestock production sector. The FAO report “Towards responsible livestock future” recommends a revitalized role for the public sector, in concert with private and non-state actors, in promoting research, investment, institutional support and governance for a responsible livestock future (FAO, 2009). The former minister of Agriculture, Nature and Food Quality in the Netherlands has made a policy agenda for sustainable livestock. In that context various initiatives intend to make the nutrient cycling via animal feed – animal manure more tight (‘sluiten van voer-mest kringlopen). There is also a renewed interest in manure processing and in the recovery of nutrients from animal manure.

2.2 Expected changes in livestock production in the Netherlands till 2020

The future is uncertain, but can be explored through scenario analyses. Recent studies suggest that the livestock sector in The Netherlands will remain stable or decrease and that the associated NH_3 emissions will further decrease significantly or will slightly increase (Janssen *et al.*, 2006; Vrolijk *et al.*, 2008). In the study of Janssen *et al.* (2006), there were four scenarios for the period 2002-2040 (Table 1). The study of Vrolijk *et al* (2008) explored two scenarios for the period 2006-2020 (Table 2). Evidently, the two studies deal with different periods and in part different scenarios. Scenario B in the study of Vrolijk *et al* (2008) is considered to be a more realistic scenario than scenario A. Scenario A in the study of Vrolijk *et al* (2008) is similar to the Global Economy scenario in the study of Janssen *et al* (2006), but the periods differ. The Global Economy scenario presumes economic growth and strong international co-operation in economic sense. The scenario ‘Strong Europe’ also presumes strong international co-operation, but this cooperation also addresses environmental issues as discussed further in paragraph 3.

Table 1 Relative changes in livestock number and NH_3 emissions between 2001 and 2040 using four scenarios (Janssen et al., 2006).

Scenarios	Number of dairy cows, %	Number of pigs, %	NH_3 emissions, %
Strong Europe	-5	-55	-30
Global Economy (GE)	+25	-5	+15
Regional Economies	-15	-55	-30
Transatlantic market	-5	-5	+5

Table 2 Total number of livestock (in million), total N and P excretion (in million kg) and emissions of NH_3 , $PM_{10,}$ CH_4 and N_2O (in million kg) in the reference year 2006, and relative changes for two scenarios for the year 2020 (in %) (Vrolijk et al.,2008).

Item, in million	Reference (2006) Millions	Scenario A (GE), %	Scenario B, %
Dairy cows	1.42	+16	0
Young stock	1.13	-25	-10
Veal calves	0.84	-13	-9
Other ruminants	2.17	-14	-8
Fattening pigs	5.48	-3	+2
Sows	1.23	-15	+4
Layers	43.00	-5	0
Broilers	42.00	-5	0
Total N excretion	462	-2	0
Total P excretion	166	-2	0
Total NH_3 emission	117	+1	-9
- housing	46	-13	-11
- manure storages	3	+19	+19
- Grazing	7	-7	-3
- manure application	31	+22	-12
Particle matter PM_{10}	8.2	0	+14
Methane (CH4) emissions	415	+2	+3
Nitrous oxide emissions	30	-3	-7

The increase in number of dairy cows in the Global Economy scenario (Table 1) and scenario A (Table 2) is related to the abolishment of the milk quota regulation in the EU and the expected relative strong position of the dairy sector in the Netherlands. The relative strong decrease in the number of pigs (and poultry; not shown) in two scenarios (Table 1) is related to the expectation that the pig sector (and poultry) in the Netherlands can not compete with pig growers (and poultry growers) elsewhere in the world (especially in Brazil and Malaysia. Further, the pig and poultry growers may not be strong enough to compete with the dairy sector in the Netherlands regarding the disposal of animal manure to agricultural land. Under these assumptions, NH_3 emissions decrease strongly (by 30%). The changes in NH_3 emissions between 2006 and 2020 are relatively small in the study of Vrolijk *et al.* (2008), due to counteracting effects in the development of livestock numbers. Emissions from grazing animals and housed animals (in part because of the adaptations in livestock housing) are expected to decrease, while emissions from manure application increase in one scenario.

The study of Vrolijk *et al.* (2008) also explores various (packages of) measures to decrease NH_3 emissions (Table 3). The packages include one or more of the following measures (i) low emission manure application on grassland, (ii) low-protein pig feeding, (iii) low-emission dairy housing, (iv) air scrubbers in pig and poultry housings, (v) low-protein feeding of dairy cows, (vi) less N fertilizer, (vii) manure digestion for biogas generation, (viii) water vapor and oil spraying in pig and poultry housings. The results presented in Tables 1, 2 and 3 provide a range of possible outcomes for the future, but are not blueprints. In most cases, emissions of NH_3 will decrease by up to about 30%.

Table 3 Emissions of NH_3, PM_{10}, CH_4 and N_2O, and the sector gross values added for the reference year 2006 and scenario B for 2020, and the changes in emissions and value added for a range of measures and packages of measures (Vrolijk et al., 2008).

Scenarios	Emissions (in million kg)				Value added Million €
	NH_3	PM_{10}	CH_4	N_2O	
Reference (2006)	117	8.2	415	30	5199
Scenario B	107	9.3	429	28	3867
Less animals (-10%)	-7	-11	-11	-4	-7
Less animals (-25%)	-15	-25	-9	-25	-15
Less N excretion (10%)	-7	-13	-9	-4	-3
Less N excretion (25%)	-16	-33	-9	-23	-11
Package 'Agriculture'	-9	-18	-4	-27	-3
Package 'Nature'	-33	-81	-7	-5	-17
Package 'Health'	-16	-85	-1	-3	-11
Package 'Climate'	-6	-0	-6	-29	-2

The results suggest that carefully chosen packages of technological measures are more effective in decreasing emissions and at lower costs than volume measures (less animals, less N excretion), especially the emissions of NH_3 and PM_{10}. However, a decrease in animal N (and P) excretion may have additional synergistic effects, which are not considered here, apart from the assumed lowering of the urea-milk content. The measures discussed in Vrolijk *et al*., (2009) are described in general terms only, and the overall effects are still rather uncertain. The present report aims to further specify the technical measures with which effective reductions can be achieved in view of the 3 P's and taking into account developments in livestock production.

2.3 Possible additional development in livestock production

The aforementioned scenarios incorporate a range of possible future developments and packages of measures (see Tables 1, 2 and 3). However, there are also possible future developments which have not been addressed explicitly in the scenarios, and yet seem important. These possible developments are discussed further below and include:

- Anaerobic digestion of manure for biogas production
- Manure processing, including separation of solid and liquid fractions, ultra-filtration, reverse osmosis, drying, incineration;
- Biofuel production, and related changes in feed concentrates;
- Bio refinery of feedstuff, separation of protein, cellulose, phosphorus;
- Changes in feed composition ('space feed') and additives
- Coupling feed production to animal production in Northwest Europe (currently explored by EL&I[1]);
- Coupling feed production to animal production at global scale (currently explored by EL&I);
- Increasing global meat consumption
- Animal welfare regulations;
- Changes in milk quota system and pig and poultry manure production quota;
- Changes in the prohibition period of manure applications;
- Changes in nature conservation (Nature 2000 areas)
- Changes in emissions sources, spatial planning and shelterbelts.

Anaerobic digestion of manure

There is an increasing interest (in part because of subsidies) to digest animal slurries in installations for the production of biogas (CH_4). Further, there is increasing interest in the (co-) digestion of all kinds of biowastes and maize silage. The effects of increasing (co-) digestion on NH_3 emissions will be discussed in chapter 4.

[1] EL&I: The Ministry of Economic Affairs, Agriculture and Innovation, The Netherlands

Pig and cattle slurry processing
There is also an increasing interest to process the animal manure so as to improve the quality and or to find new ways for its disposal, including export. Common techniques include the separation of pig and cattle slurries in a solid fraction with a dry matter content of 20-30% and a liquid fraction with a dry matter content of 1-2%. The solid fraction may be dried further to 80 to 90% or applied to land as solid manure. The liquid fraction may be processed further via ultra-filtration and reverse osmosis to produce a high-concentration liquid and an effluent that can be discharged to surface waters or to the sewage systems. Alternatively, the liquid fraction is directly applied to land. Evidently, this processing changes the slurry characteristics and its NH_3 emissions potential. Further, the processing itself is a potential source of NH_3 emissions. As yet, little is known about the overall net effect of slurry processing on NH_3 emissions (still under study).

Poultry manure incineration
There is also an increasing interest in the incineration of dried poultry manure for the production of bioenergy and for its disposal. Currently, the new power plant in Moerdijk has a capacity to process poultry manure (and other bio-energy sources) which is equivalent to about 8 million kg P2O5, which is equivalent to about 25% of the total poultry manure production in the Netherlands. The incineration plant likely has facilities to trap all flue gases, including NH_3 gases. Given the air cleaning treatment of the power plant and assuming logistics of manure transport are optimal, storages are covered and field emissions are prevented, it is likely that emissions are reduced, at least not increased, compared to the current reference situation.

Biofuel production and related changes in feed concentrates
There is also interest in producing biofuel from cereals (ethanol) and from oil seeds (bio-diesel). The interests in biofuel production fluctuate with the crude oil price and the provision of subsidy. In 2007-2008 there was a large interest in biofuel production, because of the high crude oil prices and governmental targets to produce a certain percentage of energy through biofuel. In the mean time, the crude oil prices have gone down, but the governmental targets for biofuel production in EU and US still remain high. The residues of the biofuel production in general end up in concentrates for animal feeding. These residues have a relatively low protein quality and relatively large NH_3 emissions potential. The implication for the feed industry of developments in biofuels were recently discussed at a symposium (Doppenberg and van der Aar, 2007).

Bio refinery of feedstuff
There is increasing interest in the bio refinery of all kinds of biological materials through biotechnological processes, which can be characterized by the term ‘bio-economy’. As a consequence, new ingredients will become available for the animal feed companies. Similarly, there are on going experiments with biorefinery of feed stuff (grass, soya bean) with the aim to increase the feeding value of this feed stuff and to extract components from the feed stuff which can be used for other applications with higher economic values. The effects of biorefinery on the NH_3-emission reducing potential are as yet unclear, but can be large when the bioeconomy developments will be really booming because animals can be fed according to need (Sanders *et al*., 2010).

Changes in feed composition (‘space feed’) and additives
Scientific research and competition between feed companies leads to innovative developments in the composition of animal feeds. Such developments lead to more balanced rations and to lower feed conversion ratios. An example is the introduction of the patented Air Line® feed for pig fattening by Cehave Landbouwbelang. Such feeds lower the manure production and N excretion per kg meat produced, and thereby lower also the NH_3 emissions potential as far as urinary N excretion is reduced. Similar developments are taking place in the development of concentrates for (dairy) cattle (e.g. Reijs, J., 2007; Van der Stelt, B, 2007). Evidently, there is a large potential for decreasing the NH_3 emissions potential from animal manure through innovations in animal feeds.

Certain additives may also contribute to lowering feed conversion, increasing animal health and animal performance, and lowering the NH_3 emissions potential. The innovations in feed additives for lowering the NH_3 emissions potential have been modest though (see also chapter 3). However, the out phasing or decreasing maximum concentration of certain additives like Cu and Zn in pig and poultry feed by governmental regulations and anti-microbial growth stimuli (antibiotics) will lead to increases in feed conversion and hence to increasing the NH_3 emissions potential.

Increasing global meat consumption
Steinfeld *et al*. (2006; 2010) describe an increase of the meat consumption of the BRIC countries leading to a new global market situation.

Animal welfare regulations;
Animal welfare standards have been implemented by the EU through a number of Directives, including "Animals kept for farming purposes (EU Directive 98/58/EC) i.e. the 'general framework directive'; Laying hens (EU Directive 99/74/EC); Calves (EU Directive 91/629/EEC as amended by Directive 97/2/EC); Pigs (EU Directive 91/630/EEC and Directives 2001/88/EC and 2001/93/EC). These Directives have also been implemented in national legislations. Especially the regulations dealing with animal housing have effects on feed conversion, manure production and NH_3 emissions potential. In general, animal welfare regulation, especially more freedom to move and more space resulting in larger areas per animal, may lead to a larger emitting area and an increase in NH_3 emissions potential. Giving animals litter for comfort, foraging or dustbathing behaviour increases the risk of production of methane and nitrous oxide.

Changes in milk quota system and pig and poultry production quota
The production of milk and the production of pigs, eggs and poultry are regulated through quota systems in the Netherlands. These quota systems will be abolished by 2015. Forecasts suggest that milk production (and the number of dairy cattle) will increase while the number of pigs, broilers and layers may decrease when the quota systems have been deleted and no counteracting measures have been implemented (see also paragraph 2.3 and Tables 1 and 2). Evidently, changes in quota systems and any other governmental regulation which affects livestock number in The Netherlands may have a significant impact on the NH_3 emission potential. This holds also for the regulations laid down in the Action Programs of the EU Nitrates Directives, and possibly in the water basin management plans of the EU Water Framework Directive. Such action and management plans may ultimately affect the livestock number and hence the production of animal manure and its NH_3 emissions potential (Baltussen *et al*., 2010[a+b]; Silvis *et al*., 2009).

Changes in the prohibition period and techniques for manure application;
As part of the fourth Action Program of the Nitrates Directive, the time frame for the application of animal manure has been shortened. Also, certain techniques for the application of animal manure do not have the certificate of 'low-emission application technique' anymore. Shortening the time period of manure application to the growing season only may increase the NH_3 emissions potential, because of the higher temperature during the growing season compared to late winter/early spring and late fall. Out phasing manure application techniques with a low emission abatement percentage will contribute to a decrease in NH_3 emissions. The overall net effect of the changes in the regulations for manure application is as yet unclear.

Coupling feed production to animal production at regional scale
One of the constraints of current livestock production in The Netherlands (as well as in some other regions and countries in the EU and the world) is the fact that a large fraction of the animal feed is imported from elsewhere, while the manure with most of the nutrients produced from the intake of this animal feed is not returned to the sites where the animal feed was produced. As a consequence, the intensive livestock production systems contribute to nutrient depletion in areas where the animal feed is produced and to nutrient enrichment and gaseous nitrogen emissions in areas where the animal feed is consumed for animal production (see e.g. Chapter 5 in Milieubalans 2009).

The Ministry of Economic Affairs, Agriculture and Innovation, The Netherlands (EL&I) is now exploring the possibilities and consequences of a coupling of feed production and animal production at regional scale. The ultimate aim of such coupling at regional scale is the recycling of nutrients, including nitrogen and phosphorus. A first step in such coupling may the replacement of soya cakes imported from Brazil and US by protein-rich feed stuff produced in northwest Europe. Such a change may have consequences also for the composition of animal rations, feed conversion and manure production, including changes in the NH_3 emissions potential.

Changes in nature conservation policies; zone and effect oriented approaches
In and near sensitive nature areas, atmospheric nitrogen deposition should be reduced. Farms that are situated at short distances from nature areas should carefully evaluate the impact of expanding their farm on the environment even when the maximum emission reducing techniques are being

applied. In the near future it may be possible to take into account closing farms in the neighborhood to calculate the net effect of all planned sources and the resulting N load and its impact on the specific nature values (plant species and their critical loads) that should be protected (Taskforce Stikstof/ammoniak i.r.t. Natura 2000, 2008; Beheerplan Natura 2000 Peelgebieden, 2010). Models to calculate these loads should be validated and improved and user friendly versions should be made available for farm planning purposes.

Dispersion approaches
The dispersion of ammonia from point sources like animal houses can be influenced by technical means. By increasing the stack height of the ventilation outlet and the air velocity at the outlet, ammonia can be diluted to a larger extend and transported over longer distances. Deposition on nature areas at shorter distances can be reduced in this way.
By shelterbelts (trees and small bushes) a larger part of emitted ammonia can be caught at close distance and another part can be projected at higher levels above the trees. Effects of shelterbelts are difficult to quantify, highly variable in time and dependent on characteristics of plants, season (leaf development), wind speed, wind direction and atmospheric conditions (Asman, 2008; Dijk *et al.*, 2005; Hofschreuder, 2008; Oosterbaan *et al.*, 2006).

Management with less grazing
There is an increasing trend to zero-grazing systems, in which dairy cattle are housed whole year round, and fed with mown fresh grass and silages. Currently, some 10-20 % of the dairy cattle are in zero grazing systems (housed all year round) and this percentage is increasing in time.
Commonly, the diet of housed animals is more under control and the protein content of the diet is lower than in the case of animals that are grazing in pastures. Also, the milk production level per dairy cow is higher when housed because of the improved feeding strategy with more balanced rations. Yet, the NH_3 emissions are much higher (factor 2-4) for housed animals than for grazing animals, despite the lower N excretion rates. The higher NH_3 emissions are the result of the higher NH_3 emissions for manure in housing systems and the field-application of this manure compared to the urine (and faeces) directly dropped on pastures by grazing animals.

3 Emissions of ammonia from manure

3.1 Processes of ammonia volatilization

To reduce ammonia (NH_3) emission from livestock manures, various measures have been taken in The Netherlands during the last two decades and additional measures may have to be taken in the near future. These measures interfere with the processes of NH_3 production and volatilization. To be able to better understand how the different measures affect NH_3 emissions, this chapter shortly describes the processes involved.

Ammonia is mainly produced from urea and uric acid present in animal manures. Basically, NH_3 volatilizes from the surfaces of the manures, whether in manure storages, applied to grassland or arable land or simply from the dung and urine dropped on pasture. The hydrolysis of urea or uric acid in the slurry to NH_3 can be written as follows:

$$CO(NH_2)_2 + H_2O \longrightarrow 2NH_3 + CO_2 \qquad (1.1a)$$
$$C_5H_4N_4O_3 + 4H_2O + 1.5\ O_2 \longrightarrow 4NH_3 + 5CO_2 \qquad (1.1b)$$

An extensive overview of the algorithms determining NH_3 volatilization from buildings and storages based on resistance during transport processes is described by Sommer *et al.* (2006). Here a more simple model based on gradient approach is given where NH_3 volatilization from manure is proportional to the difference between the NH_3 concentration at the surface of the manure, and the concentration in the air above the surface (Chardon *et al.*, 1991):

$$E = k\,(c_m - c_a) \qquad (1.2)$$

in which E is the volatilization rate of NH_3 (g m^{-2} s^{-1}), k the diffusion coefficient for NH_3 in air (m s^{-1}), c_m the NH_3 concentration at the manure surface (g m^{-3}), and c_a the NH_3 concentration in the atmosphere above the manure surface (g m^{-3}).

The concentration at the surface of the manure (c_m) depends on the chemical equilibrium between aqueous ammonium ($NH^+_{4,aq,m}$) and aqueous NH_3 ($NH_{3,aq,m}$) in the manure (Freney *et al.*, 1983):

$$NH^+_{4,\,aq,m} \longleftrightarrow NH_{3,\,aq,m} + H^+ \qquad (1.3)$$

The formation of gaseous NH_3 in the manure depends on the equilibrium between aqueous NH_3 ($NH_{3,aq,m}$) and gaseous NH_3 ($NH_{3,g,m}$) in the manure (Freney *et al.*, 1983):

$$NH_{3,\,aq,m} \longleftrightarrow NH_{3,\,g,m} \qquad (1.4)$$

Bussink *et al.* (1994) showed that the concentration of gaseous NH_3 ($NH_{3,g,m}$) increases with an increase of the concentration of aqueous ammonium ($NH^+_{4,aq,m}$), the pH and the temperature of the manure.

The volatilization of NH_3 from manure ($NH_{3,g,m}$) into the air ($NH_{3,g,a}$) can be described by:

$$NH_{3,g,m} \rightarrow NH_{3,\,g,a} \qquad (1.5)$$

Equation (1.2) can thus be transformed into:

$$E = k[(NH_{3,\,g,m}) - (NH_{3,\,g,a})] \qquad (1.6)$$

The factors that affect volatilization of NH_3 from field-applied manure and the emission of NH_3 into the atmosphere are described by Huijsmans, (2003) and can be grouped into three main categories:

1. chemical and physical properties of manure;
2. meteorological factors;
3. interaction between manure and the soil and crop, on which it is applied;

Groenestein (2006) made an inventory of factors affecting NH_3 emission from stored manure inside houses and grouped them as follows:

1. animal-related factors (age en weight of the animals, feed- and water intake);
2. environment-relating factors (housing configuration, air temperature and air velocity);
3. factors related to manure composition.

These two lists of factors inevitably overlap.

3.2 Pathways to reduce ammonia emissions

Reduction of NH_3 emissions can be realized by influencing the different pathways in the process of NH_3 volatilization. Table 4 gives the factors influencing the different pathways with the corresponding equations they affect. The Focus of measures to be taken to reduce emissions are presented in Table 5. It shows where present measures affect NH_3 production and volatilization in the whole manure chain: housing, storage and application. Per pathway different measures can be taken to mitigate NH_3 emissions given the key factors (Table 4). These measures are given in Chapter 4.

Table 4 Key factors affecting the volatilization of NH3 from manure during storage and after application, and the pathways from Table 4.

	Factor	Equation	**Storage and Application**
Manure properties	pH	1.3	+
	TAN [a] content	1.1	+
	Dry matter content	1.1/1.5	+/-
	Surface area	1.5	+
	Crustation [b]	1.5	-
Meteorological factors	Air temperature	1.3/1.5	+
	Solar radiation	1.3/1.5	+
	Air speed	1.5	+
	Rainfall	1.1/1.5	-
	Relative humidity	1.5	0/-
			Application
Crop and soil properties	Presence of crop residues [b]	1.5	+
	Soil moisture content	1.5	0/+
	Infiltration rate	1.5	-
	Cation Exchange Capacity (CEC)	1.3	-
	Soil pH	1.3	+
	Crop height	1.5	-

\+ denotes that an increase of the magnitude of the factor increases NH_3 volatilization.
\- denotes that an increase of the magnitude of the factor decreases NH_3 volatilization.
[a] TAN, total ammoniacal nitrogen ($NH_4^+ + NH_3$).
[b] The factors marked with a ([b]) are either present or absent; the effect of the presence of the indicated factor is denoted as + or -, when the presence of the factor increases or decreases NH_3 volatilization, respectively.

Table 5 Focus of measures in the process of NH3 production and – volatilization and corresponding equations where measures act to mitigate emission at different parts of the manure chain.

		Housing storage	Application	Pasture
1	Concentration of urea/uric acid	X	X	X
2	Production of NH4+ from urea/uric acid	X		
3	Conversion of NH4+ to NH3	X	X	X
4	Concentration of NH4+ and NH3	X	X	
5	Exchange manure and air	X	X	
6	Scrubbing NH3 from air	X		

4 Measures to reduce ammonia emissions

This chapter discusses three categories of measures for decreasing NH3 emissions from livestock manures in animal houses, manure storages and pastures, and following application to land, namely
- Proved techniques and systems;
- Promising techniques and systems, currently in research;
- Possible future techniques and systems not in research or just exploratory.

Proved techniques are techniques that are proven to be efficient in reducing ammonia emissions. These techniques are not necessarily included in directives or other administrative measures to promote adoption.
Measures to reduce ammonia emissions are discussed for (i) animal housing, (ii) manure application and (iii) pastures. As indicated before, techniques and systems for manure storage are well-developed and are not discussed further here.

4.1 Housing

Tables 6, 7 and 8 show proved NH_3 emission reducing techniques. Most of these techniques are listed in the Rav, the Dutch Directive on ammonia emission from livestock (Rav, 2010). It also shows which process(es) in the course of NH_3 production is affected by this technique in housing systems for cattle, pigs and poultry. Because of risk of pollution swapping, effects of the listed techniques on emissions of odor, particulate matter, nitrous oxide and methane are also evaluated.

As mentioned in the introduction, Planet is one of the three P's. To reconcile the economic and social values, animal health, animal welfare, working conditions and energy use were also addressed. In the following chapters measures and the pathways in reducing NH_3 emissions are described in more detail and the main pathways are emphasized by mentioning them in the paragraph titles. Techniques are described in general. Some techniques have only been studied or implemented in one animal category but may also be useful in other animal categories. The applicability of each technique for cattle, pigs and poultry is further addressed in chapter 5.

4.1.1 Proved ammonia-emission reducing techniques and systems

Fully covering the slurry pit with a solid floor *(Equation 1.5)*
Reducing the transfer of NH_3 from the slurry to the pit air by preventing air exchange between the above- floor animal room with the under-floor slurry pit is crucial in this system. In practice this measure is applied in cattle housing (Braam *et al.*, 1997[a]). The slurry pit is covered by a solid floor that is provided with openings only at the floor ends, where the faeces collected by a scraper are dumped into the pit. To minimize air flow in the pit, these openings are provided with hanging rubber flaps. The closure of the slurry pit is expected to decrease the air velocity within the slurry pit (boundary) as well as the exchange of air (m3/h) between the pit and the house, thus decreasing the volatilization of NH_3 produced in the pit. Airflow over the slurry in the pit, induced by temperature differences between the outside and the inside air (outdoor versus pit air temperature), have been supposed to be the driving force for emissions from the pit. Pit emissions are only eliminated with certainty if all air exchange between pit and house is prevented. When the air exchange rate is reduced, the concentration of $NH_{3,g,a}$ in the slurry pit will increase and its gradient with the manure concentration of gaseous NH_3 will reduce and this will reduce volatilization.

If the pit is covered with a non sloping solid floor, the emission from the floor is higher then from non-sloped floors, because both the area and the width of the urine puddles (in between the faeces) is maximized. Therefore, solid, double sloped floors provided with a central urine gutter and a scraper were developed (Braam *et al.*, 1997[b]; Rav numbers 1.2, 1.3 and 1.4) . To facilitate a quick removal of urine, the slope of the floor should be 2-3% towards the urine gutter in the centre. Manure is removed from the solid floor at least every 2 h with a scraper with a rubber strip. Part of the urine drained is collected in the urine gutter, potentially reducing NH_3 production on the floor surface by (a) reducing the width (volume) of the urine puddles, by (b) reducing the duration of exposure of the fresh urine to urease activity on the floor surface and by (c) reducing duration of exposure to the air flowing over the floor.
Systems in the Rav vary with respect to the available m^2 floor area per animal and the presence or absence of an additional water flushing system. The flushing system is mainly intended to reduce

slipperiness of the floor[2] at low water usage but also will dilute urine on the floor and manure in the pit to some extend.

Another variant of the fully covering of the slurry pit with a solid floor is the parallel grooved floor with small perforations for quick drainage of urine (Swierstra *et al*., 2001). Apart from reducing NH_3 emissions by interfering with Eq. 1.5, it also reduces breakdown of urea on the floor by quick removal (Eq. 1.1).
By using a solid floor NH_3 emissions from the slurry pit can be reduced to a large extent. The alley floors should provide a stable surface for the animals to walk on. The surface texture of the floor surface should be slip resistant to support the animals' movement. Slip resistance in the direction of the axis of the elements is further assured by the grooves. Recently a variant with also some surface profiling in perpendicular direction is designed to further reduce the risk of slipping on this floor.

Cooling the manure *(Equation 1.3, 1.4 and 1.5)*
Ammonia emissions from manure storage systems can be reduced by cooling the upper layer of the manure with floating cooling elements. The heat extracted from the manure could be upgraded with a heat pump to be used for heating purposes elsewhere. The cooling water is cooled either in a soil heat exchange system or by means of a heat pump. It is important that this system is working continuously, even when the transferred heat cannot be used directly. In the latter case, surplus heat should be stored within the soil. By cooling, the dissociation of NH_3 (Eq. 1.3), the transfer from liquid to gas phase (Eq. 1.4) and the volatilization from manure to air (Eq. 1.5) are slowed down (Starmans & van der Hoek, 2007). Cooling the slurry with the floating elements is not reliable when slurry develops a floating layer with high dry matter content like cattle manure or pig manure from pigs fed a high fibre diet.

Reducing the emitting surface *(Equation 1.5)*
The main working principle of this ammonia reducing system is the reduction of the emitting manure surface area (m^2/animal place). This reduces ammonia emission by reducing the transfer from slurry to air (Eq. 1.5). Besides the permanently emitting slurry pit surface area, the above pit floor area that can be covered with fresh urine puddles to some extend should be distinguished. If the floor area covered by urine puddles is also reduced, a lower conversion of urea to ammonia (Eq. 1.1) on the floor can be expected because the surface area where conversion occurs is smaller and the interval time between urinations on the befouled surface is reduced. The question remains whether this mechanism is a limiting factor at this stage to contribute to an emission reduction.
Reduction of the emitting manure surface area can be realised by: 1) reducing the manure pit area by increasing the solid floor area; 2) placing slanted plates in the manure pit; 3) separating the manure pit in compartments with a high manure load and with a low manure load. The latter can be combined with dilution with water and thus affecting volatilization rate as described by Eq. 1.2.

In this system, it is essential that, while reducing the emitting surface area of the manure, the fouling of other parts of the pen should not increase. This is especially critical when the slatted floor area is reduced and the solid floor area is increased. This is the reason why reducing the manure pit area is merely applied in pig housing because of the excreting behaviour of pigs, who tend to create an excreting corner rather then cattle, who excrete everywhere. A well designed pen and a good indoor climate is essential to induce this 'toiletting' behaviour of pigs (Aarnink *et al.*, 2006). New pen designs have been developed to reduce fouling of the floor (Aarnink *et al.*, 1996; Hacker *et al.*, 1994; Hol and Satter, 1998; Reitsma and Groenestein, 1995). By using cooling systems pen fouling during the summer can be prevented (Huynh *et al.*, 2004).

When slurry is stored in V-shaped gutters underneath the slatted floor, frequently removing the manure reduces the emitting surface. This way ammonia transfer from slurry to air (Eq. 1.5) is

[2] The solid floors that cover the slurry pit were produced and tested without further profiling the surface of the floor However, the risk of slipping on the floor appeared to be higher than on a slatted floor, especially when a thin film of manure attaches (by drying) to the floor when the cows go outdoors during grazing. After coming back into the house, this film will be wetted with urine and the floor may become extremely slippery. With several types of bi- or multidirectional profiles in the floor surface, this problem can be solved. However emission is likely to be higher with such profiles because fouling of the floor is increased, as are the resulting emitting surface and the volume of urine retained on the floor.

reduced. The manure gutters should cover the whole manure pit and be made of a corrosive free material, e.g. poly-ethylene. The walls of the gutter should have a slope of at least 60^o, a V-shape (not an U-shape) and a depth of 20 – 60 cm. In the approved systems in the Rav, the fresh manure should be flushed at a minimum frequency of two times a day.

Quick removal of separated urine and faeces *(Equation 1.5)*
Recently a new system for separation and quick removal of faeces and urine from the pit was tested (Aarnink *et al*., 2007[a]). The basis is a special steel construction and the use of slightly V-shaped manure belts. When using the V-shaped manure belts urine can run of immediately, separating it from the faeces, which is once daily removed from the animal house. This reduces ammonia emission by reducing the transfer from slurry to air (Eq. 1.5). The conversion of urea is likely to be also reduced especially at low temperatures (Eq. 1.2).

Acidification of slurry *(Equation 1.3)*
Ammonia emission in this system is reduced by collecting fresh urine and faeces in an acidified liquid. The conversion of NH_4^+ to NH_3 (Eq. 1.3) is reduced to a large extend at low pH. Also the breakdown of urea by urease (Eq. 1.1) may be reduced when the low pH reduces development of urease producing bacteria. It is not known weather this reduction of urease activity is reduced to an emission-reducing level.
The mixture of urine, faeces and acidified liquid is regularly removed and replaced by new acidified liquid. The acidified liquid is obtained by separating the faeces particles from the liquid part, followed by an acidification step to a pH below 6. The layer of fresh acidified liquid should be at least 5 to 10 cm high and the flushing should be done with a frequency of at least once every two days. The pH of the liquid at the time of removal should not be higher than 6.5. Broadcast application of acidified manure was not recognized as a low emission application technique in the nineteen's because it was difficult to uphold by controllers.

Dilution of slurry *(Equation 1.2)*
Lowering the concentration of ammonia and ammonium is an effective way of reducing ammonia emission. However, when the slurry is diluted with water, the consequently increased volume of slurry makes this option not economically suitable as a general measure for commercial farms. Only in pit parts with a low manure load it is suitable, e.g. the small slurry channel behind the feed rack in pig pens. The Rav also describes a diluting system by adding Kapto ® to the liquid phase of slurry. The concentration of ammonia is reduced because it is chemically attached to formaldehyde. Due to health risks which can be caused by volatilization of formaldehyde, this solution is not realized in practice.

Poultry litter drying *(Equation 1.1)*
By quickly drying poultry manure the aerobic breakdown of uric acid (Eq. 1.1) and undigested proteins can be prevented to a large extend because at low moisture content growth of microbes is limited. This implies lower production of microbial enzymes catalysing production of NH4+ from uric acid and protein. On-site drying of poultry manure can be realised in many ways. In most systems, the manure is dried on belts using air that is heated by the heat production of the animals. Litter systems can also be equipped with a drying system (Ellen *et al.*, 2005; Aarnink *et al.*, 2007[b]; Groot Koerkamp & Groenestein, 2008).

Poultry litter removal *(Equation 1.5)*
By regularly removing the poultry excreta, dried or not, to a closed storage area, ammonia emission is strongly reduced. Belt systems can be used to transport manure to such centralized storage areas. At the storage the manure can be dried and or the volatilization can be reduced by controlling temperature and air velocity (Ellen *et al.*, 2005; Aarnink *et al.*, 2007[b]).

Poultry litter cooling *(Equation 1.1)*
Bacterial activity and the resulting breakdown of uric acid (Eq. 1.1) is reduced by cooling the floor and the litter on top of it (Groot Koerkamp, 1998). Without the cooling, the manure heats up, caused by spontaneous composting of the manure as a result of bacterial activity.
The floor can be equipped with heat exchange elements filled with water. In broilers, warm water is used in the first week of the growing period, when the young birds need higher temperatures. From day 21 onwards, cold water is used to cool down the floor and the litter on top of it (Aarnink *et al.*, 2007[b]).

Air scrubbers *(Pathway 6)*
The most common end of pipe ammonia abatement technique is the application of an air scrubber system for the removal of ammonia from the exhaust air from animal houses (Table 4, pathway 6). Both biological and acid based scrubbers can be used. Ammonia removal rates of these systems are 70-95%. Air passing a chemical or biological scrubber is also purified with respect to dust and pathogens. In combined air scrubbers a chemical washing section precedes a biological washing section. In this way also odorous compounds can be eliminated from the treated air (Melse *et al*., 2009).

Reducing dimensions of scrubbers *(Pathway 6)*
By installing a bypass in ventilation systems, a limited proportion of the air is not treated when ventilation is at or near its maximum capacity. This maximum ventilation capacity is only applied in a limited number of days and therefore costs per reduced kg ammonia can be significantly lowered while net reduction is only little less (Melse *et al.*, 2006; Ellen *et al*., 2008[a]).

Reducing ventilation requirements *(Pathway 6 and Equation 1.5)*
By reducing ventilation requirements, systems like scrubbers can be designed smaller and costs per reduced kg of ammonia can be lowered. Ventilation requirements can be reduced by reducing the heat load on the building (insulation) or by conditioning the incoming air (e.g. heat exchanger like in Ellen *et al*., 2008[b]).
Development of closed housing systems with minimized emissions is a promising approach. This by designing the house and the ventilation system (optionally using heat exchangers) such that the ventilation requirements are minimized and episodes outside the thermo comfort zone are reduced. Ammonia volatilization is also reduced by reducing air velocity and temperature at the emitting surface.
In this way a larger emission reduction and a higher cost effectivity can be obtained in many animal categories. Although high producing dairy cattle do have the highest ventilation requirements this approach combined with air scrubbing may be competitive with other emission reducing techniques. Especially on sites where a high emission reduction is required e.g. near nature areas with a high protection level (e.g. Natura 2000) this may give dairy farmers the possibility to continue their activities.

Lowering air velocity *(Equation 1.5)*
Air velocity can be lowered when the ventilation requirement is reduced (see former paragraph). In naturally ventilated houses automatically controlled natural ventilation (ACNV) can be installed to reduce the air velocity both at the boundary between floors and surrounding air and in the pit especially at high outdoor wind speed. In pig houses air velocities may be reduced by adding screens in the pit to prevent high air velocities over the emitting surfaces. In cattle houses this may also be considered. However, pit slurry mixing in cattle houses should not be complicated by installing screens.

Indoor air scrubbing *(Pathway 6)*
Melse and Ogink (2004) suggested that by scrubbing part of the air inside the animal house, air quality in the animal environment can be improved and emissions from the animal house of NH3, odor and particulate matter can be reduced The dimensions of such a scrubber can be optimized to benefit both the indoor and outdoor environment and the cost efficiency. Such a system can be further optimized by additionally cooling the air. In that way the ventilation requirements can be reduced and the proportion of the air treated in the indoor scrubber can be increased. When indoor air scrubbing with wet scrubbers is considered, limitations in recycling of the humid air that leaves the scrubber should be paid special attention.

4.1.2 Overview of promising techniques and systems, currently in research

Rubber topped floors *(Equation 1.1 and 1.3)*
Several types of rubber topped floors in cattle housing are being tested in experimental animal houses for dairy cattle. Floors topped with other flexible synthetic materials are also being developed. The floors may reduce ammonia emission by reducing the urease activity and thus the breakdown of urea (Eq. 1.1), because less bacteria are developed on the surface (Smits & Bokma, 2008). Furthermore,

the pH of the urine puddles on such top layers may be reduced by 0.1 – 0.3 units (Eq. 1.3) compared to urine puddles on concrete slatted floors.

Slatted floors with flexible flaps *(Equation 1.5)*
Flexible synthetic flaps in slatted floors reduce the transfer of ammonia from the slurry to the pit air by closing the openings between the slats. Only during excretions and during passage of excreta from a scraper the space between the slats will be opened like a valve by the weight of the excreta. The primary impact is covered by Eq. 1.5. When air exchange is reduced, the concentration of $NH_{3,g,a}$ in the slurry pit will increase and its gradient with the manure concentration of gaseous ammonia will reduce and this will reduce volatilization from the manure.

Profiled solid floors *(Equation 1.5)*
Because the first generation of emission reducing floors in dairy cattle appeared to become slippery, recently floors with different profiles were developed. Some of these floors will be tested in pilot animal houses. A profile is not expected to reduce emission as much as smooth floors. The amount of urine and faeces that is kept in the profiles will likely result in a slightly higher emission (Smits, 1998). However, these floors may be better accepted in practice and therefore adopted on a larger scale which could result in a substantial progress in emission reduction at a national scale.

Solid floor without underfloor pit *(Equation 1.5)*
When there is no pit underneath the slatted floor in the cow house, obviously emissions from the pit are zero. Slurry cannot be stored and must be removed from the house, usually with scrapers, and stored in a covered outside storage. This variant will be tested in 2011-2012 in commercial cow houses. It can be seen as a variant of covering the slurry pit with a solid floor that is intended to reduce the emitting surface.

Urease inhibitors *(Equation 1.1)*
Normally, urease is available in abundance in urine puddles on the floor and is not a limiting factor in the breakdown of urea into ammonia. Urease inhibitors reduce the activity of the enzyme urease or block the enzyme completely. Reduction of ammonia volatilisation by applying urease inhibitors on floors in Dutch cow houses has only been studied in a few experiments more than a decade ago. Recently, tests with some new inhibitors showed promising results. However the performance at farm scale still has to be demonstrated (Smits & Bokma, 2008). Urease inhibitors also can be applied just before slurry application. A substantial emission reducing effect can only be expected when urea is not broken down in earlier parts of the chain. This is especially relevant when urea breakdown is reduced or prevented in the animal house or during outdoor storage.

Acidification of slurry *(Equation 1.3)*
Ammonia emission is reduced by acidifying the whole volume of slurry that is stored underneath the animal housing. The conversion of NH_4^+ to NH_3 (Eq. 1.3) is reduced to a large extend at low pH. Also the breakdown of urea by urease may be reduced when the low pH reduces development of urease producing bacteria. In the past prototypes of a system were tested in The Netherlands where only a small part of the separated liquid fraction of slurry was recycled in pig houses as described in 4.1.1. Recently a Danish company has made a more practicable system for common pig houses that have deep slurry pits (Kai *et al*., 2008). In this system, the slurry is pumped to an outdoor intermediate storage where the sulphuric acid (H_2SO_4) is added. Next the slurry is pumped to the pig house again. Within common cow houses with slurry channel circuits, the system with controlled acidification can be integrated without an intermediate outdoor storage. The acidification of slurry in the animal house also may help to reduce emissions after slurry application in the field and improve plant N utilisation.

Pit air separation and treatment *(Equation 1.5 / Pathway 6)*
In dairy cattle houses, air removal from the pit by forced ventilation of a limited volume is studied at pilot scale. The separated pit air with high concentrations of ammonia, odours and probably also a small proportion of particulate matter can be treated by chemical or combined (chemical and biological) air scrubbers. The potential of the system has already been tested in a veal calf house (Smits *et al*., 2008). Results were promising. An advantage of the system is that the indoor air quality for the animals and the people is also improved when polluted air from the pit is removed in this way. In pig houses the system may also be useful.

Use of litter *(Equation 1.3 and 1.5)*
In free range systems for poultry, litter is often used. The physical and chemical properties of litter influence the ammonia emission. By either choosing a certain type or modifying an existing litter, the ammonia abatement properties can be enhanced to suit the needs. Recently Van Harn *et al.* (2009) compared emissions from small broiler housing units with different bedding materials and showed that silage maize had approx. 50% lower ammonia emission compared to wood shavings, wheat straw and rapeseed straw. It was hypothesized that the maize silage resulted in a lower pH of the bedding by microbial production of fatty acids. Also very fine dust (PM2.5) emission was reduced with maize silage bedding, probably due to its high moisture content.
Cattle research has recently been started to study effects of different bedding (sand, compost and clay) on ammonia emissions from freestall housing systems without pit underneath the solid floor. Emissions will depend on infiltration rate of urine, available area per animal and urine production per animal (production level and diet), cultivation of the top layer, composting rate and resulting temperature, air velocity at the top layer, etc. There is an increased risk for N_2O emissions by nitrification and denitrification when in deep litter both a lower layer with low or no oxygen and a top layer with normal oxygen content by natural aeration develop.

Applying oil or water *(Equation 1.5)*
Spraying oil or water in animal houses is primarily intended to reduce particulate matter emissions. However gaseous emission may also be reduced to some extend, especially ammonia and odor molecules that are attached to small particulate matter. However, in a first experiment in Spelderholt (Lelystad) poultry house Cambria-Lopez *et al* (2009) did not find any effects on ammonia emissions. In an earlier experiment Aarnink *et al* (2008[b]) also concluded that ammonia emissions from broiler rooms were not affected by the oil treatment. The effect on odor emission can not be excluded, but is still in research.
Aarnink & van Harn (2010) recently reported a desk study to determine whether the oil film technique could be combined with additives that reduce ammonia emission and optionally also odor emissions. Aluminum sulfate and aluminum chloride were identified as promising additives to the litter in layer housings by Aarnink & van Harn. When a water film is used for dust reduction, aluminum sulfate or aluminum chloride could be applied as a solved compound in the water. When an oil film is used for dust reduction aluminum sulfate or aluminum chloride could be applied on the litter in the same run of a mobile system. In broilers, the additive could also be added to the litter at the start of the growing period as is done in the US (Aarnink & van Harn, 2010; Moore *et al*., 1995, Celen *et al*., 2008).
Besides spraying oil in the animal room it is also an option to apply a thin covering layer of oil on top of the slurry in the pit (Derikx & Aarnink, 1993; Derikx *et al*., 1995). This is mainly applicable on pig slurry that has a smooth top layer. To maintain a full covering layer of oil on top of slurry, temporarily spraying of additional small amounts of oil may be necessary. In an experiment ammonia emission from a pig house unit was reduced 45% with a liquid top layer of oil in the slurry pit. Prevention of loss of oil during slurry withdrawal is crucial both from the economical and environmental points of view. The oil spraying equipment and the logged spraying times can be easily inspected and controlled.

Dietary measures: reduced protein content and/or feed additives *(Equation 1.1)*
Total N excretion, Total Ammoniacal N (TAN) content and pH of urine and slurry can be reduced by changing the composition of the diet and by applying specific additives to the diet (Canh *et al*., 1997; 1998; Bakker & Smits, 2001; Tamminga *et al*., 2009). In pigs, benzoic acid is evaluated as an emission reducing additive (Aarnink *et al*., 2008[a]). In cattle reduction of bulk milk urea content was recognized as an indicator of ammonia emission reduction. Because protein content of the diet of dairy cows is high, this pathway seems to be promising. In pigs and poultry the surplus of protein in the diet is not that large, but can also be reduced. Possibilities for inspection and control (law enforcement) in pigs are being developed in 2009-2010 (Aarnink personal communication).
Also diets with a larger proportion of carbohydrates that ferment in the hindgut may help especially in pig nutrition by shifting excretion of nitrogen from urine (quickly degradable urea) to faeces (slowly degradable microbial protein). With bacterial fermentation in the large intestine also volatile fatty acids (VFA) are formed. These VFA lowers the pH of faeces and of manure (Canh, 1998[b]; 1998[c] and 1998[d]). Optimizing N digestion of the diet may also help reducing ammonia emission (Tamminga *et al.*, 2009).

4.1.3 Overview of possible future techniques and systems

Ionization *(Pathway 6)*
By ionization of air, particles in the air are getting a negative or positive electrical charge. These electrical charged particles are attracted to grounded surfaces, e.g. walls and equipment inside the animal room and will attach to these structures. Especially dust particles in the air can be captured in this way. Research in poultry farms in other countries suggested that this may also have a reducing effect on ammonia emission (Mitchell *et al.*, 2004, Ritz *et al.*, 2006). Reported effects were highly variable. In a pilot in a broiler house of ASG, Cambra-López *et al*. (2009) did not find any effect on ammonia and odor emissions with this technique that succeeded well in reducing particulate matter emissions. The technique is mainly applicable in forced ventilated buildings. Safety is an issue. Ionization should not have effects on the animals and the electronic equipment in the house.

Ozone *(Pathway 6)*
The ‘free’ oxygen molecules in ozone are capable to react with other gases in the air including ammonia. This results in simple compounds. Reductions in ammonia emission of 15-58% were reported (Patterson and Adrizal, 2005). At high concentrations ozone can be dangerous. The MAC-value is 0.120 gram for a maximum of one hour. If and under what conditions ozone can be safely applied to reduce ammonia emission, needs to be studied further.
In a pilot on a commercial pig farm application of UV radiation and ozone resulted in an improvement of the technical performance of the animals that was related to reduced incidence of diseases.
The ozone generators had a shorter lifetime than expected and the costs were high due to the high dust concentrations in the pig house. Therefore research on the application of ozone was stopped at that time (Sleurink, 2001). Recently, however ozone application combined with dust reduction techniques has received new attention. It is not yet known whether significant amounts of nitrate or secondary particles (fine dust) are produced as a byproduct of this technique.

Photo catalytic oxidation *(Pathway 6)*
By photo catalytic oxidation in the presence of UV-light, anorganic and organic compounds, including NH_3, can be broken down (Costa and Guarino, 2008, Guarino *et al.*, 2007). However, reported results with NH_3 are highly variable. Starmans and Ogink (2008) stated that application of a TiO_2 coating on walls in animal houses, combined with internal air circulation might be an option in forced ventilated buildings. A restricted contact time and contamination of the coating by attachment of particles are probably the most limiting factors. However knowledge is insufficient yet to make a final judgment on the feasibility .

Manure separation and processing *(trend)*
By separation of urine and faeces in the animal house or by creating a liquid and a solid fraction after quick removal of slurry from the animal house, fractions can be obtained that can be applied or further processed and than be applied as replacers of chemical fertilizers and as N rich and P rich fractions that can be distributed at lower costs. Pilots have recently been started in the Netherlands to test the performance of different separation and further processing techniques and the crop mineral utilization and the environmental impacts. Further developments in this area may have substantial effect on future manure management, housing systems and resulting ammonia emissions.

Ammonia sensor *(feedback)*
When it would be possible to monitor emissions at commercial farms at low cost and with a high reliability an effect oriented governmental policy could be defined. Then it would be possible to give farmers a lot more freedom in choosing the optimal (combination of) reduction measures. A direct feed back of the resulting ammonia emission to the farmer may act as a positive stimulus. These systems, however, are not yet available.

Integrated farm level approach *(management)*
At the moment permits for farms, especially when scaling up, are mainly based on the animal houses and their emissions. Present Dutch and EU regulations do not allow to judge ammonia emissions at farm level. However in future this approach may be considered, especially when emissions in the whole manure chain can be controlled in this way. The farmer than is more flexible in investments and management choices to meet requirements.

A method to reduce ammonia losses is reducing the number of animals by increasing milk production per cow. By improving longevity of dairy cows and breeding sows the number of young animals kept for replacement can be reduced. With prolonged lactation the number of calvings can be reduced. By helping farmers to improve their operational management skills and stimulating good management by amended legislation an integrated farm level approach can be strengthened (Aarts *et al.*, 2007).

Pit air treatment and ammonia stripping *(Equation 1.5 / Pathway 6)*
An interesting and innovative concept might be to strip the ammonia from the slurry in the pit (indoor) or from an outdoor manure storage by aeration and/or by increasing the air velocity above the slurry. The ammonia rich air is next removed from the pit headspace and led through an acid scrubber. The collected N than can be applied as a fertilizer and the risk of N loss in the whole chain is controlled. When this concept is applied in an animal house with a slatted floor, flow of air with high concentrations of gasses from the pit trough the slatted floor at the same time should be prevented for animal health and welfare reasons. This could be done by maintaining underpressure underneath the slats or by cooling the pit air (temperature difference). When valves are installed between the slats or when a solid floor is placed above the slurry pit, there is only little or no air exchange to the animal occupied room. When aeration is applied nitrous oxide emissions might increase thus the aeration should be well controlled. Volatilization of components from the slurry other than ammonia (e.g. odorous compounds) should be controlled. For this reason application of a multi stage scrubber with an acid trap, a water trap and a biofilter should be considered.

Table 6 Proved ammonia emission reducing measures in housing systems for cattle, reduction % compared to traditional system, effective parameters and effect on odor, particulate matter, nitrous oxide and methane addressing animal health and –welfare, working conditions and energy use. Effects on odor, particulate matter, nitrous oxide and methane emission in this table and the following tables are indicated as: 0: no effect, +: increase, -: decrease/reduction, ? : not yet clear what the effect will be.

Proved ammonia emission reducing measures	**NH_3 emission reduction %**	**Urea concentration**	**Degradation of urea**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+/NH_3**	**Exchange manure – air**	**Absorbing NH3 from air**	Odor emission	Particulate matter	Nitrous oxide	Methane
Fully covering the pit with a solid floor	15-30					X		-	0/-	0	-
Fully covering the pit with a solid floor with a flushing system	15-35				X	X		-	0/-	0	-
Parallel grooved floor system and perforations for quick urine drainage	15-35		X			X		-	0/-	0	-

Animal health and welfare impacts are dependent on the quality of the floor: slipperiness may increase the risk of locomotion disorders. Rough floor surfaces may increase the risk of too high pressure and wearing of tissues of the digit (claw). Flexible rubber or plastic top layers are being developed to tackle these risks.
Working conditions are influenced in different ways: solid floors will improve air quality in the cow house. With solid floors the good functioning of manure scrapers is crucial. Regular maintenance of the scraper and cables is important. A substantial risk of occasionally required reparation increases the work load. With robot scrapers this risk may be lower.
Direct energy use on solid floors is higher than on slatted floors because of manure scrapers.

Table 7 Proved ammonia emission reducing measures in housing systems for pigs, reduction % compared to traditional system, effective parameters and effect on odor, particulate matter, nitrous oxide, methane addressing animal health and -welfare, working conditions and energy use.

Proved ammonia emission reducing measures	**NH_3 emission reduction %**	**Urea concentration**	**Degradation of urea**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Exchange manure-air**	**Absorbing NH3 from air**	Odor emission	Particulate matter	Nitrous oxide	Methane
Cooling the manure surface	30-50			X		X		-	0	0	-
Reducing the emitting surface	20-50					X		-	-	0	0
Quickly removal of excreta by flushing V-shaped gutters with liquid manure	25-50					X		-[1]	-/0	0	-
Separation of urine and feces & quick removal (Aarnink *et al*., 2007[a])	50-80					X		-	0	0	-
Acidification of slurry	30-65			X				+/- [2]	0	0[3]	-
Dilution of slurry	10-30				X			-	0	-	-
Scrubbers	70-95						X	-	-	0	0
Reducing ventilation requirements	10-30					X		-	-	0	0

(1) A disadvantage of this system may be that during flushing peak odor levels can be high although the overall average odor emission might be reduced.
(2) Acidification may give high peak odor concentrations when starting up and after delayed acidification, also the hedonic tone may be adversely affected
(3) When H_2NO_3 would be used, N_2O emissions may increase

Animal health and welfare are not directly affected by the 'below floor' measures because these measures are not affecting the animal occupied zone.
Working conditions are influenced in different ways: all measures except scrubbers will improve air quality in the pig house. The good functioning of equipment may be assured by regular maintenance. The risk of occasionally required repairment only little increases the work load because these measures are not directly affecting the animal occupied zone and therefore there is no high urgency for repairment; a technician from elsewhere can be hired. Only with acidification of slurry special care is needed when the equipment is restarted after longer term defects.
All measures will result in a higher energy use (equipment). Only in case of cooling the manure surface the net energy use may be improved by utilizing the heat gained from the manure e.g. to preheat water.

Table 8 Proved ammonia emission reducing measures in housing systems for poultry, reduction % compared to traditional system, effective parameters and effect on odor, particulate matter, nitrous oxide, methane, addressing animal health and -welfare, working conditions and energy use.

Proved ammonia emission reducing measures	**NH_3 emission reduction %**	**Uric acid concentration**	**Degradation of uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Transfer from liquid to air**	**End of pipe air treatment**	Odor emission	Particulate matter	Nitrous oxide	Methane
Litter drying	40-70		X					-	+	0	0
Manure belt drying	40-80		X					-	0	0	0
Litter removal	50-80		X	X	X	X		-	-	-	-
Litter cooling	40-50		X					+/-(1)	0/-	-	-
Scrubbers	70-95						X	-	-	0	0
Reducing ventilation requirements	10-30		X	X		X	X	-	0/-	0	0

(1) If cooling results in higher wateractivity, odor emission may be higher

Animal health will be improved by litter drying or litter removal, because ammonia concentrations will be significantly lower at the animal level (micro climate) Specially in broilers the incidence of sole lesions will be reduced (feet quality improves) by litter drying. If litter cooling results in higher water contents, sole lesions may increase. Animal welfare may be adversely affected by litter removal because (4) dust-bathing behaviour is temporarily impossible
Working conditions may be influenced by litter drying by a higher risk of increased particulate matter concentrations. Energy use will be higher when litter drying, removal or cooling is applied. However, innovative systems that are using heat produced by the animals for heating and geothermic heating and/or cooling have been and are being developed. By reducing ventilation requirements energy use can also be reduced.

Table 9 Ammonia emission reducing measures in housing systems in research, expected reduction % compared to traditional system, effective parameters and expected effect on odor, particulate matter, nitrous oxide, addressing animal health and -welfare, working conditions and energy use

	ammonia emission reducing measures in research	**NH_3 emission reduction %**	**Urea / uric acid concentration**	**Degredation of urea/uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Exchange manure - air**	**Absorbing NH3 from air**	Odor emission	Particulate matter	Nitrous oxide	Methane
Floor /pit	No slurry storage underneath the animal house (mainly in cattle)	0-50					X		-	0/+	-	-
	Rubber/synthetic material topped floors (mainly in cattle)	0-15					X		0/-	0	0	0
	Slatted floors with flexible flaps closing the pit (mainly in cattle)	10-25					X		-	0	0	0/-
	Synthetic material topped floors with flexible flaps closing the pit (eg mat & valve)	10-50					X		-	0	0	0/-
	Profiling solid sloping floors that cover the pit (mainly in cattle)	-20-0*					X		0/+	0	0	0
Diet	reducing pH of urine (mainly in pig diets)	15-40			X				+/-	0	0	-
	reducing pH of faeces (mainly in pig diets)	5-20			X				0/-	0	0	+
	Reducing digestable N surplus in diet (and farm N surplus)	20-40	X						-	0	0	0
	Shift from urinary N to faecal N (mainly in pig diets)	5-30	X						0/+	0	0	+
	Combined diet effects (mainly in pig diets)	30-60	X		X				+/-	0	0	+/-
Additives	Use of different litter material(s) (poultry)	0-50		X	X				0	0/-	?	0
	Use of different litter material(s) (cattle)	?		X	X				?	?	?	?
	Urease inhibitors	15-30		X					0	0	?	0
	Acidification of slurry (pigs and cattle)	20-60			X				+/-	0	0	-
	Spraying oil or water in the house (poultry, pigs)	0-15					X		0	--	0	0
	Covering oil layer on top of the slurry in the pit	0-60					X		0/-	0	0	0

ammonia emission reducing measures in research	**NH_3 emission reduction %**	**Urea / uric acid concentration**	**Degredation of urea/uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Exchange manure - air**	**Absorbing NH3 from air**	Odor emission	Particulate matter	Nitrous oxide	Methane
Air treatment & ventilation											
Pit air scrubbing: pit air separation and treatment (pigs and cattle)	15-60						X	-	0	0	0
Reducing dimensions of scrubbers (air scrubber with bypass)	50-70						X	-	-	0	0
Reducing air velocity	10-30					X		0/-	-	0	0
Ionization	0-30							0/-	-	0	0

* Profiling is done to reduce the risk of slipping and may increase the ammonia emission compared to a non profiled floor. However, the success of emission reducing concepts like covering the slurry pit is also depending on its animal welfare impact. Without profiling there is a negative impact (locomotion disorders). When profiling is combined with other measures the net effect is likely to be an emission reduction.

Measures that reduce emissions from the pit have a positive impact on animal health and working conditions because concentrations of NH3 and other gases will be lower in the animal room.
Measures that improve the grip on the floor (profiling or flexible top layer) for cattle or pigs will improve animal welfare (natural locomotion and behaviour) and animal health (leg disorders and digital disorders).

Table 10 Future possible ammonia emission reducing measures in housing systems, expected reduction % compared to traditional system, effective parameters and expected effect on odor, particulate matter, nitrous oxide, methane, addressing animal health and -welfare, working conditions and energy use.

Future possible ammonia emission reducing measures	**NH_3 emission reduction %**	**Urea / uric acid content**	**Degradation of urea/uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Transfer from liquid to air**	**End of pipe air treatment**	Odor emission	Particulate matter	Nitrous oxide	Methane
Indoor air scrubbing (partial recirculating and optionally cooling air)	?						X	-	-	0	0
Pit air treatment and ammonia stripping	30-70						X	-	0/-	+/0/-	-/0
Ozone	?						X	-	-	?	0
UV	?						X	-	-	?	0
Photo catalytic oxidation of NH_3 (UV + TiO_2 coating)	?						X	-	-	?	0
Management		X	X								
NH_3 sensor for feed back to improve management and optionally stearing of emission reducing equipment	?										
Combining measures											

The effect of indoor air scrubbing is depending on the dimensions of the scrubber, the proportion of the air that is treated, the distribution of concentrations of gases within the animal room and its variations and the adequate positioning of the air inlet of the scrubber. The advantage of an indoor scrubber is that it is not an end of pipe technology: it will also have a positive impact on the indoor air quality. A disadvantage is that it is likely to result in a lower removal rate, but with an adequate positioning this disadvantage can be reduced.

4.2 Application

As with housing the control of the process of volatilization after manure application to farmland interferes with the mechanisms, which underlie this process. Three main strategies can be defined to reduce ammonia volatilization when applying manure: (1) lower the ammonium (NH_4^+,aq,m) concentration in the manure (Eq. 1.2), (2) reduce the formation of gaseous ammonia (NH3,g,m) by lowering the pH (Eq. 1.3) and (3) decrease the diffusion of gaseous ammonia (NH3,g,m) by decreasing the contact area between the manure and the atmosphere (Eq. 1.5).
Any change in the composition of the manure in the housing or storage may affect the ammonia emission after manure application onto the field. This interdependence within the manure chain is described by Huijsmans et al. (2001) and Groenestein et al. (2010). Next to these changes, specific measures can be used for manure application. Lowering the ammonia concentration in the manure can be achieved by dilution of the manure. Lowering the pH of the manure can be achieved by adding acid to the manure, either in the store, just before application on the field, or during application. Increasing the infiltration of the manure into the soil can be achieved by irrigation or changing the fluidity characteristics of the manure. Decreasing the exchange contact area of the manure can be achieved by the application technique or by improving the infiltration of the applied manure into the soil.

4.2.1 Proved ammonia-emission reducing application techniques

In the Netherlands, all three strategies to reduce ammonia volatilization were considered. Dilution of the manure and acidification were less feasible, because these measures were difficult to check in practice by supervising authorities. Much effort was put into the improvement and development of techniques for the application and incorporation of manure. The search for new techniques was mainly based on decreasing the contact area between the manure and the atmosphere, thus interfering with Eq. 1.5. The approach for manure application on grassland was different from that on arable land.

4.2.1.1 Grassland

Injection of manure into the soil seemed to be a good application technique on grassland. However, injection requires a high draught force, and may reduce herbage yield due to sward damage by the tines and crop die-back along the injection slots. This and the remnants of tree stubs in the soil often make injection impossible. Therefore, new techniques for manure application, with low ammonia volatilization, were developed for grassland.

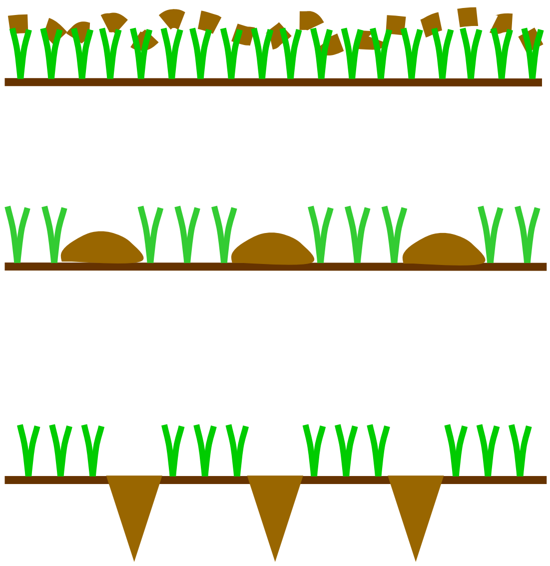
With these new techniques, either a shallow slit is cut into the sward and the manure is applied into the slit (shallow injection), or the manure is applied in narrow bands onto the soil surface using a trailing-foot implement. These techniques require low draught force compared with conventional deep injectors (Huijsmans *et al*., 1998, Figure 1).

Broadcast surface spreading is not approved. It used to be carried out by a tanker fitted with a splash-plate. The manure was pumped through an orifice onto a splash-plate from where it was spread onto the soil and the grass. The net working width was about 8 m.
Narrow-band application is carried out by trailing narrow sliding feet (also called ‘shoes’) over the soil surface, pushing aside the grass cover but not cutting the sward. Each foot is horizontally by a parallelogram construction. Manure is released at the back of the feet leaving narrow bands of manure onto the soil surface. The bands have a width of about 0.03 m and are spaced 0.20 m apart. Contamination of the grass with manure is negligible. A tanker may be equipped with 25 trailing feet with a total working width of 5 m (Huijsmans *et a*l., 1998).
Shallow injection (open slot) is carried out with injection coulters. Coulters and discs are used to cut vertical slots into the grass sward. Manure is released into the slots, which are left open. The slots are up to 0.05 m deep and are spaced 0.20 m apart. Depending on the application rate, the slots are more or less filled with manure. Unlike the conventional deep injector, shallow injectors have no lateral wings and do not cut the soil horizontally underneath the sward (Huijsmans *et al*., 1998).

Narrow-band application and ***shallow injection*** significantly reduce NH_3 volatilization, compared with broadcast surface spreading. The mean cumulative volatilization for surface spreading is

estimated to be 74% of the total ammoniacal nitrogen (TAN) applied, 26% for narrow-band application and 16% for shallow injection (Huijsmans and Vermeulen, 2008).
Huijsmans *et al*. (2001) showed that the volatilization rate increased with an increase in TAN content of the manure, manure application rate, wind speed, radiation, or air temperature. It decreased with an increase in the relative humidity. The identified influencing factors and their magnitude differed with the application technique. Grass height affected NH_3 volatilization when manure was applied in narrow bands. The results show that external factors need to be taken into account when predicting ammonia volatilization following manure application.

.



Broadcast surface spreading. Manure spread on top of the grass. NH_3-N emission = 0.74 TAN

Narrow band application by trailing shoe (or foot). Manure in bands on top of the soil between the grass leaves. NH_3-N emission = 0.26 TAN

Shallow injection open slot. Manure in slots in the grass sod. NH_3-N emission = 0.16 TAN

Figure 1 Manure placement in grassland. The traditional system of broadcast surface spreading of slurry is not allowed anymore in The Netherlands. It is shown here to visualize differences between application techniques.

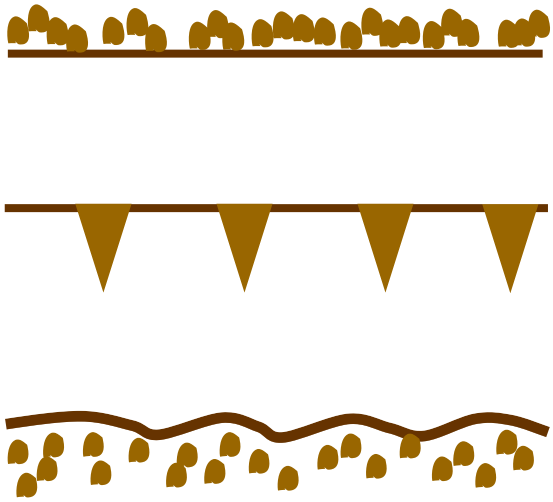
4.2.1.2 Arable land

The presence of a crop hampers the incorporation of surface-applied manure on grassland. On arable land, however, incorporation of surface-applied manure is a readily available technique. Various incorporation techniques are commonly available on farms. Incorporation of manure may be combined with soil tillage. Manure could also be injected into arable land. Research was carried out to asses the effectiveness of different incorporation techniques to reduce ammonia volatilization. In the case of incorporation after manure application, the effect of a time-delay between manure spreading and incorporation needed to be assessed, because ammonia volatilization from surface-applied manure peaks the first hours after spreading (Huijsmans & De Mol, 1999).

Ten different application techniques or incorporation techniques are analysed in field experiments on their effect on the ammonia volatilization. The techniques could be suitably grouped into three application methods, based on their positioning of the manure on or into the soil (Figure 2).

Broadcast surface spreading is not approved by the government. It used to be carried out with a tanker fitted with a splash-plate. The manure is pumped through an orifice onto a splash-plate from where it is spread onto the soil. The net working width is about 8 m.
Surface incorporation is defined as the treatment by which manure was surface spread and, subsequently, incorporated into the soil. Conventional tillage implements (cultivators with rigid tines, spring tines, discs, or harrows) are used to incorporate the surface-applied manure into the topsoil directly following the surface spreading.
Deep placement is defined as the treatment by which the manure is buried in the soil, either directly by an injector or indirectly by ploughing with a mouldboard plough directly after surface spreading. An arable land injector is equipped with spring tines, which place the manure directly underneath the soil

surface at a depth of 15 to 20 cm. At the same time the injector carries out a tilling operation by covering the manure with soil.



Broadcast surface spreading. Manure spread on top of the soil. NH_3-N emission = 0.69 TAN

Shallow injection open slot. Manure in slots in the soil. NH_3-N emission is unknown

Incorporation of surface applied manure or injection of manure. NH_3-N emission = 0.02-0.22 TAN

Figure 2 Manure placement arable land

The mean total volatilization, expressed as % of the total ammoniacal nitrogen (TAN) applied, is estimated to be 69% for surface spreading, 22% for surface incorporation and 2% for deep placement (Huijsmans and Vermeulen, 2008). Huijsmans *et al.* (2003) showed that the volatilization rate increased with an increase in TAN content of the manure, manure application rate and air temperature. Wind speed had a substantial effect on the volatilization rate, only when manure was surface applied or surface incorporated.
The reduction of NH_3 volatilization can be achieved by incorporation of the manure into the soil; the degree of reduction depends on the method of incorporation. Direct burying with a mouldboard plough (deep placement) yields more reduction of NH_3 volatilization than incorporation by a rigid tine cultivator (surface incorporation). However, in practice on whole field scale, direct incorporation is not always achievable. There will always be some time between surface spreading and incorporation and during this time volatilization of NH_3 from the surface-applied manure takes place. Huijsmans & De Mol (1999) showed in a model study that incorporation by a mouldboard plough does not always result in lower NH_3 volatilization than incorporation by a rigid tine cultivator. The model study of Huijsmans & De Mol (1999) showed that the time-lag between spreading and incorporation should be considered when assessing NH_3 volatilization from manure applied and incorporated on arable land. In case of deep placement by injection the time-lag is zero and low volatilization rates can be achieved, as shown in the present study. In the Netherlands surface spreading followed by incorporation by a second tillage operation is not allowed any more since 2008 for liquid manures; all liquid manure should be injected (arable land injector or shallow injector as for grassland) or spread and incorporated in one operation. Solid manures still need to be incorporated directly after application.

Shallow injection (open slot as approved for grassland) is also an approved application technique for arable land; for this technique no NH_3 emission data are available for bare arable land; it may be expected that the NH_3 emission after shallow injection on bare arable land is different from shallow injection on grassland.

4.2.2 Overview of promising application techniques currently in research

4.2.2.1 Crops

Manure application in crops becomes more common in the Netherlands, because manure application in autumn and early winter is not allowed any more on arable land on clay soils. Manure application in for instance wheat crops should be carried out by shallow injection. To prevent crop damage, it is discussed whether the manure should be shallow-injected or that narrow band application should give sufficient emission reduction. Recently the first measurements on NH_3 volatilization after applying manure (shallow injection versus narrow band application) in a wheat crop in spring time were carried out.

Currently new methods for manure application in crops, like potato and maize, are in development. These application techniques mainly focus on preventing crop-damage; control of ammonia emission is in discussion.

4.2.2.2 Processed manure

Pilots have recently been started in the Netherlands to test the performance of different separation and further processing techniques, the crop mineral utilization and the environmental impacts. Recently research is started to use the treated manure as replacement of chemical fertilizer. First measurements of ammonia emission after application of high concentrated (high TAN content) treated manure are started when applying it in wheat, potato and on grassland.

4.2.2.3 Diet and weather conditions

Weather conditions directly after manure application affect the height of the ammonia emission. It is discussed how farm management by diet and timing of manure application (emission reducing weather conditions) can help to control ammonia emissions. For a group of farmers their management and timing of manure application (broadcast application) is monitored and the effect on the ammonia emission is assessed.

4.2.3 Overview of possible future application techniques and their effects on emissions

4.2.3.1 Bare arable land

As mentioned in the former paragraphs no emission factors are available for shallow injection on bare arable land. It is a proved application and it becomes more implemented in practice. It was recommended to start research on the emission factors for better assessment of the ammonia emission as this method is well implemented in common practice (Velthof *et al*., 2010).
Direct incorporation of manure on arable land is prescribed since 2008. Direct incorporation can be achieved by 1. injection (direct deep placement) or 2. in one operation surface application and incorporation (the incorporation equipment is connected to the tank for the manure application); these two methods result in different emission factors. Optimization of the direct incorporation may help to further reduce ammonia losses.

4.2.3.2 Crops

Manure application in crops will become more common due to the narrower time-windows for manure application. Manure application in crops (underneath a canopy) may become more applicable to manage manure application in terms of logistics. Currently new methods for manure application in crops, like potato and maize, are in development. These application techniques are mainly focussed on preventing crop-damage. To control ammonia emissions it is discussed how to effectively place or incorporate the manure between the potato ridges. Crop canopy may be a way to further reduce ammonia losses.

In maize precise manure application in the crop row is an innovative option to better utilise manure (especially on sandy soils). This will lead to locally (the row) concentrated manure application and thus higher loads at a smaller area. Common application systems will need to be adapted to this row application within the constraint that ammonia emission needs to be controlled.

4.2.3.3 Grassland

Since the introduction (and first measurements) of shallow injection on grassland in the early 90’s a tendency was found of higher ammonia losses with this application technique over the following years (Huijsmans and Vermeulen, 2008). Changes in the technique or different use of the technique (for example higher application rates) may be the cause of these higher losses. A break of this trend or finding the causes to return to lower emissions may help to further decrease ammonia losses.

In the near future narrow band application on sandy soils will not be allowed any more, because a good alternative is available (shallow injection). Narrow band application in early spring time is in discussion as field conditions to make the band spreader pushing aside the grass are hardly met. Favoring/stimulating shallow injection on clay soils may help to further reduce ammonia losses. Conditions should be that way that soil and crop damage is prevented. Alternatives for peat soils may be considered.

4.2.3.4 Field and weather conditions

For a further reduction of ammonia volatilization following manure application on grassland and arable land next to the application methods also characteristics of the manure, soil and weather conditions during and after manure application should be taken into account to find the best emission reducing conditions. Taking into account these characteristics and conditions the present proved application techniques could be used more efficient in a way of achieving even more reduction of ammonia losses (Huijsmans, 2003). To find the best conditions a model approach in combination with conducted measurements in the past seems to be the best method for the assessment of the best weather and soil conditions to control emissions after manure application. Currently, available models for this assessment are being reviewed.

4.2.3.5 Combination of emission reducing techniques

Next to the present applied application methods, increased reductions may be achieved by combinations of applications techniques and methods that interact with the process of ammonia volatilization; for instance by narrow band application or shallow injection of partly acidified manure (Huijsmans en Verwijs, 2008). The acidification may be carried out in the storage or batch wise just before application as described in paragraph 4.1.2.

4.2.3.6 Manure types

In the past most measurements on arable land were carried out with pig manure and on grassland with dairy manure. Dairy manure is more and more used on arable land. To meet N application budgets the volume of dairy manure applied ($m^3\ ha^{-1}$) is larger than when pig manure is applied (because the TAN content of dairy manure is lower than of pig manure). These higher volumes may cause another (higher) emission factor for manure application. This may also be the case when measures are taken to lower the nitrogen contents in the manure or when using separated or treated manures.
More treated or separated manures become available and recently research is started to use the treated manure as replacement of chemical fertilizer. Some treatments may lead to (specific) emission factors when applying that manure. Next to application rates (volume) and nutrient contents also the manure characteristics (dry matter, viscosity) may affect the ammonia losses. Further developments in this area may have substantial effect on future manure management, housing systems and resulting ammonia emissions after manure application.

4.2.3.7 Digestion of slurry

There is an increasing interest to digest animal slurries in installations for the production of biogas (CH_4). Manure digestion decreases the organic carbon, total solids and dry matter contents of the manure (slurry), increases the total ammoniacal nitrogen (TAN) content and lowers the viscosity of the slurry. The pH may also increase, depending also on the initial pH. These changes in slurry properties may have diverse (contrasting) effects on NH_3 emissions following its application to land (Huijsmans & Mosquera, 2007). A lowering of the viscosity of the slurry will increase the infiltration rate of the slurry into the soil. As a result, the NH_3 emissions may decrease. The increase in TAN content though will increase the NH_3 emissions potential. The net effect depends on the changes in slurry properties combined with environmental conditions during and following slurry spreading as well as soil conditions.

Further, there is increasing interest in the (co-) digestion of all kinds of biowastes and maize silage. This co-digestion increases the volume of animal slurry, because all material added to animal manure will legally ‘change’ in animal manure. Some of the biowastes may contain significant amounts of nitrogen, and hence TAN following digestion, while others may have low nitrogen content. The latter also holds for maize silage. The net effects on NH_3 emissions from animal manure are as yet unknown.

4.2.3.8 Solid manure

Solid manure may be surface applied on grassland. On arable land the surface applied solid manure needs to be incorporated; the incorporation takes place sometime after application; in that time emission takes place. For both solid manure application on grassland and arable land very little information is available on ammonia losses.

Tables 10-12 summarize the ammonia-emission reducing measures discussed above and also describe the expected effects of these measures on the emissions of N_2O, CH_4, odour and PM.

In case of manure application no effects of emission reducing measures are expected on animal health and animal welfare. The measures may improve working conditions due to a decrease in odor and particulate matter emissions, but also due to more hygienic conditions with well-equipped manure application techniques. Energy consumption is slightly increased in case manure is applied into the soil (higher draught force).

Table 11 Proved ammonia emission reducing measures for manure application, reduction % compared to broadcast surface spreading, effective parameters and effect on odor, particulate matter, nitrous oxide and methane.

Proved ammonia emission reducing measures	**NH_3 emission reduction %**	**Urea / uric acid content**	**Degradation of urea/uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Transfer from liquid to air**	**End of pipe air treatment**	Odor emission	Particulate matter	Nitrous oxide	Methane
Band spreading trailing foot grassland	65					X		-	0	0/?	0
Shallow injection grassland	80					X		-	0	+	0
Direct incorporation arable land (no crop)	70					X		-	0	0	0
Injection arable land (no crop)	95					X		-	0	+	0
Shallow injection arable land (no crop)	?					X		-	0	+/?	0

Table 12 Ammonia emission reducing measures for manure application <u>in research</u>, expected reduction % compared to broadcast surface spreading, effective parameters and effect on odor, particulate matter, nitrous oxide, methane.

ammonia emission reducing measures in research	**NH_3 emission reduction %**	**Urea / uric acid content**	**Breakdown of urea/uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Transfer from liquid to air**	**End of pipe air treatment**	Odor emission	Particulate matter	Nitrous oxide	Methane
Band spreading in winter wheat	30-40					X		-	0	0/?	0
Shallow injection in winter wheat	50-70					X		-	0	0/?	0
Taking into account weather conditions	30			X	X	X		-	-	0/+	0
Treated manure (grassland/ crops arable land)	50-80					X		?	0	0/+	0

Table 13 Ammonia emission reducing measures for manure application <u>in future</u>, expected reduction % compared to broadcast surface spreading, effective parameters and effect on odor, particulate matter, nitrous oxide, methane.

Future possible ammonia emission reducing measures	**NH_3 emission reduction %**	**Urea / uric acid content**	**Breakdown of urea/uric acid**	**Conversion NH_4^+ NH_3**	**Concentration NH_4^+ / NH_3**	**Transfer from liquid to air**	**End of pipe air treatment**	Odor emission	Particulate matter	Nitrous oxide	Methane
Acidification and low emission manure application	70-95				X	X		-	0	0/?	0
Weather conditions and application technique	70-90					X		-	-/0	-/0	0
High performance shallow injection or manure incorporation arable land	70-90					X		-	-	?	0
High performance shallow injection or narrow band application grassland	60-90					X		-	-	?	0
Manure application in crops (potato, maize)	>70					X		-	-/0	0	0
Treated manure, digestion, application rate and low emission application	60-80			X	X	X		+/-	0	?	0
Solid manure application (grassland) and incorporation (arable)	70					X		+/-	0	?	0

4.3 Pasture

4.3.1 Grassland & nutrient management

Bussink (1996) showed that emissions from urine patches is related to N intake by the cows. Van Vuuren (1993) and Valk (2002) showed that N intake and N excretion in urine of grazing cows may be reduced by supplement feeding with low protein high energy feedstuffs. Emission from urine patches of grazing cows is generally lower than the emission of the same urine volume in a traditional housing system and the subsequent slurry application of that urine. Most of the urine excreted during grazing is quickly infiltrating into the soil, but also very concentrated at a certain spot (patch). Therefore the volume of urine available for ammonia emission is limited. However the potential for nitrate leaching to groundwater is large (Corré, 2006).
By balancing mineral availability with crop utilization of nitrogen, e.g. a lower fertilizer rate, protein content of grass and other crops can be better controlled. This has been shown on De Marke and on Cows and Opportunities farms (Schröder *et al*., 2007). Enforced by the EU nitrate directive an approach towards mineral balancing is now being applied on a large scale on commercial farms in the Netherlands.
A further improvement may be the online determination of the actual status and the course of important processes during crop growth for roughage production. In this way the resulting contents of fresh or conserved grass in the diet can be better managed. To be able to effectively control, quick measuring methods are needed, so that information e.g. the composition and feed value of fresh grass in the field, becomes available in time. Recently new technologies have been developed that might be suitable for application in quick measuring methods for dairy farmers (Stienezen *et al.*, 2004).

4.3.2 Effect of grazing on emission from the cow house

When cows are restricted grazing, ammonia emission from a cow house with a slatted floor gradually decreases by approx 2.4% per hour that the cows are outdoors (Kroodsma *et al*., 1993; Monteny *et al*., 2001). When cows are grazing 10 hours per day the emission is approx 24% lower than when the cows are zero grazing. Emission from he cow house is not reduced very much because mostly the slurry pit has a very large remaining volume of ammonia and the ammonia from the fresh urine puddles on the floor is only exhausted several hours after the cows leave the building. The slurry collected in the cow house will also be emitting after it is applied on grassland or on arable land. Measures that reduce the N surplus of restricted grazing cows will have an emission reducing effect from the pasture, in the cow house and during slurry application.

4.3.3 Impact on milk urea

Van Duinkerken *et al* (2009) showed that bulk milk urea concentration is a useful indicator for ammonia emission reduction from dairy cow houses in a situation with restricted grazing. In this study, the p.m. milking (after grazing during the day) generally showed a higher milk urea concentration than the a.m. milking (after indoor supplement feeding during the night). This is quite common when N-rich pasture grass is grazed during daytime and cows are supplemented in the barn between p.m. and a.m. milking with feedstuffs that have a smaller N content than grass. Van Duinkerken *et al* (2005) stated that a peak in N intake with the feed causes a peak in milk urea concentration within 5 hours. By reducing the N content of the fresh grass the emission from grazed grasslands may be reduced. Emissions also may be reduced by reducing the number of grazing hours, especially in autumn when grass growth and its N contents is highly variable and more difficult to manage.

4.3.4 Out-wintering pads and semi closed outdoor exercise yards

In Ireland (French *et al*., 2008) and France (Ménard & Séité, 2009) in recent years experiments were done with low cost roofless dairy cattle accommodations (Dooren & Galama, 2009). The basic idea is that in a mild climate cattle can graze in summer but also be kept outdoors in winter. In winter, without grass growth, the animals have to be fed. The grass sod can not resist its heavy use by cows near the feeding places. Therefore a solid (concrete) floor at the feeding places seems necessary. A lying area with a soft bedding material should be refreshed regularly for cleanliness of the cows and udder health. Because of rain and mud the use and related costs of bedding material are high compared to indoor systems. In a French experiment the lying are was made up of a gravel layer with a drainage tubing system, a layer of grind and a top layer of wood shavings. The precipitated water and the diluted dung were collected in a basin. The contents of the collected fluids were analyses every 2 weeks.

For animal welfare access to pasture is recommended, especially for freedom of movement and recovery of leg and digital disorders. A semi closed outdoor exercise yard (with manure nutrient recycling) can be a compromise for animals that are mainly kept indoors. Then the animals have access to a limited outdoor area that can be managed at a high animal density while excreted urinary N can be collected in below soil drainage tubes connected to a storage facility (with or without further processing). The drainage water can be collected permanently or in periods with a high risk of nitrate leaching e.g. depending on the season and the precipitation rate. The excreted fecal N and P and other nutrients (organic matter) can be accumulated in the yard and be applied on arable land or grassland elsewhere when its contents in the yard reach a certain level. The best application practices of mixtures of soil, manure and optionally bedding materials and the soluble fraction in the drainage water needs to be studied. Application can be done with or without further processing of the solid and liquid fractions from the yard.
Depending on the soil characteristics and the water level and upward pressure it might be necessary to install a floor (concrete or synthetic layer) in the yard to prevent the risk of nutrient leaking and to block the entry of up streaming ground water.
The management of such a system may be further improved by monitoring the yard soil contents and drainage contents directly or indirectly (e.g. soil EC). The initial soil composition and the management of such an exercise yard may be adapted to minimize losses of NH3, N2O and NO3. A knowledge based system to manage such a yard could be developed. The concept needs further R&D to be applicable with minimized losses to the environment. The impacts on working conditions and energy use cannot yet be quantified and should be paid attention when the system is being further developed.

4.4 N deposition

Measures that reduce ammonia emission on a large scale are effective in reducing the impact of ammonia in sensitive natural areas. Another approach is to locally reduce deposition of ammonia in vulnerable zones like Natura 2000 sites. Factors that are influencing ammonia deposition are the dimensions and shape (geometry) of the ammonia source, the positioning of the ammonia source in relation to the positioning of the sensitive natural area, wind direction, wind speed, precipitation, terrain roughness, the canopy compensation point for ammonia of the vegetation c.q. the manure and fertilizer N load level of the area between the source and the sensitive natural area. The canopy compensation point is defined as the effective surface concentration of ammonia.

Measures that may influence these factors are: changing the positioning and distance of the emitting source, adapting the height of the air outlet(s) of the animal house, optimizing the timing of manure application in relation to meteorological conditions, changing the terrain roughness (e.g. growing different crops or trees), adding shelterbelts near the animal house that are catching some particles while projecting other particles at a higher height in the atmosphere (Hofschreuder, 2008). Some measures were already explored in model simulations: the positioning of the emission source in relation to the positioning of the sensitive natural area (Hofschreuder, 2010), the height of the air outlet of forced ventilated buildings and the air velocity in the outlet (Smits *et al.*, 2010) and the effect of shelterbelt like structures (Hofschreuder, 2008).

The ammonia concentrations and depositions can be calculated by several models (New National Model, Depac, AAgrostacks, ISL 3A, preliminary PAS tool ammonia). Because measures to reduce emission during application are generic, manure application is taken into account in the models in a general way: the back ground concentrations at 5x5 or 1x1 km are calculated with the regional data on land use and manure application techniques. However it could be interesting to study whether changing application management has a substantial effect on reducing deposition in and nearby Natura 2000 areas.

5 Research priorities

In this report a large number of measures to reduce ammonia emission have been identified. One of the aims of this study was to identify measures for research. To select these measures, priorities have to be set. Therefore three general criteria were taken into account: the potential impact on ammonia emission; the applicability in different animal categories; the early stage of research.

All the measures given in this report are summarized in Table 14 a and b, including their expected effects and the stage of research that these measures are in. It is also indicated if the measures are applicable for cattle-, pig- and/or poultry manure systems, if it has an effect throughout the manure chain and weather there is a risk of pollution swapping.

Also is considered that measures applicable in more than one animal categorie are worthwhile but in cattle the sense of urgency is highest because little progress in implementing low emission systems has yet been made on commercial dairy cattle farms and this may restrict these farms in their development considering the Natura 2000.

Ammonia emissions from manure application contribute significantly to atmospheric ammonia during the growing season. Due to changing application techniques and changing distribution of manure application over the year the impact of such changes on emissions need special attention and best practices should be defined based on measured low emission performances.

As mentioned in chapter 2, developments in agriculture, even though not primarily aimed to reduce emissions, should be taken into account. These aspect demand an integrated approach and can be listed as follows:

- litter housing systems and the application of the solid manure;
- manure separation and storage and application of the liquid and solid fractions;
- manure treatment, storage, application rate and low emission application technique;
- manure application in crops.

Table 14a Measures to reduce ammonia emission from housing, their expected effects, applicability in cattle, pigs and poultry and the stage of research per animal species. Effects are indicated as: 0: no effect, +: increase, -: decrease, ? : not yet clear, y=yes, n=no, R&D= stage of Research & Development with, F= fundamental research, P= proof of principle, V= validation monitoring on commercial farms, i= already implemented,*= not in research.

	NH_3 reduction%	NH_3 chain effect [a]	Pollution swapping [b]	Applicable in cattle	Applicable in pigs	Applicable in poultry	R&D cattle	R&D pigs	R&D poultry
Ammonia emission reducing measures in research									
Floor /pit									
No slurry pit storage underneath the animal house	++	0/-	-/0	y	y	y	V	*	*
Slatted floors with flexible flaps closing the pit	++	0/-	-/0	y	y	n	V	P	*
Reduced slurry pit surface	+	0/-	-/0	n	y	n	*	i	*
Primarily separation of urine and faeces (Aarnink *et al*., 2007[a])	++	0/-	-/0	y	y	n	P	V	*
Rubber/synthetic material topped floors (mainly in cattle)	+/0	0	0	y	y	n	V	V	*
Floor with drainage by filtering layer(s)	+/0	0/-	-/0	y	y	n	P	P	*
Diet									
Reducing pH of urine	++	++	-/0	n	y	n	*	V	P
Reducing pH of faeces	+	+	-/0	n	y	n	*	V	*
Reducing digestable N surplus in diet (and farm N surplus)	++	+++	0	y	y	y	V	V	V
Shift from urinary N to faecal N	+	0	0	n	y	n	*	V	P
Combined diet effects	+++	+++	-/0	n	y	n	*	V	V
Additives									
Litter systems & management (with optional use of different litter materials)	+/0/-	+/0/-	+/0/-	y	y	y	FPV	FPV	FPV
Urease inhibitors /additives application on floors/ in bedding	+	+/0	0/-	y	y	y	P	P	P/V
Urease inhibitors /additives application in slurry pit	+	+/0	0/-	y	y	n	P	P	*
Urease inhibitors /additives just before slurry application	+	-	0/-	y	y	y	P	P	P/V
Acidification of slurry (pigs and cattle)	++	+	0/-	y	y	n	V	V	*

	NH_3 reduction%	NH_3 chain effect [a]	Pollution swapping [b]	Applicable in cattle	Applicable in pigs	Applicable in poultry	R&D cattle	R&D pigs	R&D poultry
Spraying water with aluminum sulfate or $AlCl_3$ in the house (poultry, pigs, probably also cattle in litter systems)	+	0/-	0/-	y	y	?	FPV	FPV	FPV
Covering oil layer on top of the slurry in the pit	+	0	0/-	n	y	n	*	V	*
Floating balls layer on top of the slurry pit	+	0	0/-	?	y	n	PV	V	*
Air treatment & ventilation									
Air scrubbing	+	-/0	0	y	y	y	PV	i	i
Pit air scrubbing	+	-/0	0	y	y	n	PV	PV	*
Reducing dimensions of scrubbers (bypass)	+	-/0	0	y	y	y	V	V	V
Internal air scrubbing	+	-/0	0	y	y	y	P	PV	PV
Reducing air velocity	+	0/-	0/-	y	y	y	V	PV	*
Reducing ventilation requirements	+	0/-	0	y	y	y	PV	PV	PV
Ionization	+/0	0	0	y	y	y	P	P	P
Ozone & UV radiation	+/0	0	0	n	y	y	*	P	P
Photocatalytic oxidation of NH_3 (TiO_2 coating)	+/0	0	0	n	y	y	*	P	P
Manure separation (incl. separate storage and application)	?	?	?	y	y	n	FP	FP	*
Processing manure, reducing volume (RO, screw press, evaporation)	?	?	?	y	y	y	FP	FP	PV
Finishing animals at lower weight	+	+	0	y	y	y	V	V	V
Prolonged longevity of reproduction animals	+	+	0	y	y	y	V	V	V

a: + indicates that in the next steps of the chain ammonia emission may increase, - indicates that in the next steps of the chain ammonia emission may decrease,0 indicates that no impact on ammonia losses in the next steps of the chain ammonia emission is expected.
b: + indicates that increased pollution swapping is expected, - indicates that decreased pollution swapping is expected, 0 indicates that no change in pollution swapping is expected.

Table 14b Measures to reduce ammonia emission from manure application, their expected effects, applicability in cattle, pigs and poultry and the stage of research per animal species. Effects are indicated as: 0: no effect, +: increase, -: decrease, ? : not yet clear, y=yes, n=no, R&D= stage of Research & Development with, F= fundamental research, P= proof of principle, V= validation monitoring on commercial farms, i= already implemented.

	NH_3 reduction%	NH_3 chain effect [a]	Polution swapping [b]	Applicable in cattle	Applicable in pigs	Applicable in poultry	R&D cattle	R&D pigs	R&D poultry
In research									
Band spreading wheat	+	0	0/-	y	Y	n	PV	PV	
Shallow injection wheat	+	0	0/-	y	Y	n	PV	PV	
Field and weather conditions	+	0	0	y	Y	y	FP	FP	FP
Treated, (co)digested or separated manure	+	0	0	y	Y	y	P	P	
Future possibilities									
Manure application in crops (potato, maize)	+	0	?	y	Y	y	FP	FP	FP
High performance shallow injection or manure incorporation	+	0	0/-	y	Y	n	PV	PV	
High performance manure application on grassland	+	0	0/-	y	Y	y	PV	PV	
Weather conditions[c] ánd low emissions application techniques	+	0	0/-	y	Y	y	FP	FP	FP
Acidification ánd band spreading or shallow injection	+	0	0/?	y	Y	n	P	P	
Treated manure, application rate ánd low emission application technique	+	0	?	y	Y	y	P	P	P
Application or incorporation of solid manure (from litter systems)	?	0	?	y	Y	y	PV	PV	PV

a: + indicates that in the next steps of the chain ammonia emission may increase, - indicates that in the next steps of the chain ammonia emission may decrease,0 indicates that no impact on ammonia losses in the next steps of the chain ammonia emission is expected.
b: + indicates that increased pollution swapping is expected, - indicates that decreased pollution swapping is expected, 0 indicates that no change in pollution swapping is expected.
c: application management timing system (AMTS) *Use of additives/urease inhibitors before manure application are listed under housing*

5.1 Housing

Urease inhibitors

Aim
Quantify the longer term emission reducing effects of urease inhibitors under common farming conditions, on floors, in litter, in a slurry pit and just before manure application.

Background of research
Urease inhibitors are expected to have a large emission reducing potential and their robust application is therefore interesting to be studied in proof of principle studies for one or more animal categories. The effects could be studied in different housing systems, for different animal categories with a dose effect relationship. In a first phase this could be done in one animal category and housing system eg dairy cattle in a traditional cow house with a slatted floor and a go/no go thereafter for pigs on a slatted floor. In parallel the same approach could be followed in litter systems.

Prospects and cost efficiency
The expected emission reduction is 15-30%. Cost efficiency can be high. Although costs of robust techniques for dosing small amounts at regular intervals on floors or in slurry pits of animal houses may be high. Toxicity of inhibiotors should be documented and food safety and animal health should not be impaired.

Applicability and knowledge exchange between animal categories
Efficiency of the measure depends on floor systems and animal behaviour. These aspects need extra consideration and documentation.

Internal air scrubbing

Aim
Proof of principle in different animal houses

Background of research
Studies should take into account variations in strengths of emission source, air flow patterns within forced ventilated and naturally ventilated houses and seasonal influences. A fundamental approach of studying distributions of ammonia concentrations within buildings related to ventilation systems and air flow patterns (eg CFD modeling) might be considered in this context as well

Prospects and cost efficiency
The potential improvement of indoor air quality is appealing not only for ammonia but also for odor and particulate matter. The cost efficiency is largely depending on the dimensions of the scrubber and its removal rate. Attention should be paid to the inside humidity increase by wet air scrubbers.

Applicability and knowledge exchange between animal categories
In a first stage the proof of principle can be performed in one animal category. The experiences can be useful in later studies in other animal categories

Pit air scrubbing

Aim
Proof of principle in dairy cattle and in pigs

Background of research
Studies should take into account variations in strength of emission sources, air flow patterns within forced ventilated and naturally ventilated buildings and seasonal influences. Research efforts can be shared with the proof of principle study of internal air scrubbing, including a fundamental approach of

studying distributions of ammonia concentrations within buildings related to ventilation systems and air flow patterns (eg CFD modeling).

Prospects and cost efficiency
The potential improvement of indoor air quality is appealing. The cost efficiency should take into account the advantage this can have on animal health and the resulting profit. It also positively affects health of people.

Applicability and knowledge exchange between animal categories
In a first stage the proof of principle can be performed in one animal category. The experiences of a proof of principle in a forced ventilated veal calves housing can be useful in studies in other animal categories

Reducing ventilation requirements

Aim
Proof of principle studies and CFD studies, especially in cattle

Background of research
In pigs forced ventilation techniques and cooling/heating systems were developed to minimize energy use and to improve microclimate at animal level. In veal calves some of these techniques can be adopted. In dairy cattle heat load can be reduced and cooling systems may be considered in order to reduce ventilation requirements. When ventilation requirements are reduced, forced ventilating systems can be implemented and scrubbers can be applicable.

Prospects and cost efficiency
In houses for veal calves improvement of climate and air quality is possible. In dairy cattle houses near nature areas, emission reducing systems with high reductions are required to allow further development of farms. A cost benefit evaluation can only be made after studies have shown quantitative effects.

Applicability and knowledge exchange between animal categories
Technologies can be exchanged between animal categories. Quantitative effects and possibilities differ between animal categories.

Reduced ventilation requirements combined with air scrubbing (especially for cattle houses)

Aim
Proof of principle in cattle houses of scrubbing air to remove NH_3.

Background of research
By designing the house and the ventilation system such that the ventilation requirements are minimized and episodes outside the thermo comfort zone are reduced, investments and operational costs of air scrubbers can be reduced. Ammonia volatilization is also reduced by reducing air velocity and temperature at the emitting surface. Ventilation requirements can be reduced by reducing the heat load on the building (insulation) or by conditioning the incoming air.
This approach is interesting in all animal categories. In cattle that are mostly naturally ventilated at present, this approach may be especially worthwhile to investigate.

Prospects and cost efficiency
This technology may be competitive with other emission reducing techniques. Especially on sites where a high emission reduction is required e.g. near nature areas with a high protection level (e.g. Natura 2000) this may give dairy farmers the possibility to continue their activities. The cost efficiency is largely depending on the dimensions of the scrubber and its removal rate.

Applicability and knowledge exchange between animal categories
In a first stage the proof of principle can be performed in one animal category (cattle). The experiences can be useful in later studies in other animal categories

Slatted floors with flexible flaps closing the pit in pig houses

Aim
Proof of principle studies to test suitable design and functioning of flexible flaps (valves) in slatted floors with or without welfare friendly mats for pigs.

Background of research
In pigs the proportion of ammonia originating from the pit is larger than in dairy cattle. Preventing pit emission is therefore effective. However is must be tested weather the system is applicable with pigs. For instance the flaps should be resistant to the exploring and rooting behavior of the pigs and to the potential biting of the material. Additionally it should be tested whether the relatively low weight of the pig's excrements is sufficient to open the flaps.

Prospects and cost efficiency
Both the air quality in the animal occupied zone and the outdoor environment can benefit from reducing the emissions by flaps in the slots of the floor.

Applicability and knowledge exchange between animal categories
The environmental effect of slatted floors with flexible flaps has already been studied in dairy cattle and first results were promising.
If this solution is also applicable for pigs needs to be tested in pig pens. The system might also be interesting for veal calves and bulls.

Litter housing systems and the application or incorporation of solid manure from litter systems

Aim
Proof of principle studies to define best suitable bedding materials and bedding management practices to minimize emissions of litter systems

Background of research
Litter systems are being (cattle) or have already been studied (pigs and poultry) especially because of their expected positive impact on animal welfare. However in order to minimize emissions of ammonia and green house gases, a large research effort is needed to find suitable bedding materials and bedding management practices that meet the many requirements e.g. comfortable dry and hygienic, low cost and well controlled.
Out-wintering pads and semi closed outdoor exercise yards can be seen as a variant of litter systems and knowledge can be transferred when these systems are being developed in NL in the future.

Prospects and cost efficiency
Litter housing systems can only be implemented on a large scale when emissions are at an acceptable level and can be controlled well. Especially risk of greenhouse gas emissions must be considered. Litter systems may result in lower incidences of disorders and prolonged longevity and in this way a long term emission reduction per kg milk or meat can be achieved.

Applicability and knowledge exchange between animal categories
Basic emission processes are the same in pig and cattle litter systems. However space requirements, fouling behavior, volumes of urine and feces excreted etc differ (Aarnink, 1997, Monteny, 2000, Groenestein, 2006). Therefore emission levels and adequate solutions may differ and parallel research tracks seem reasonable.

Manure separation and further processing of liquid and solid fractions

Aim
The emission impacts of new manure treatment technologies should be quantified

Background of research
The direct separation of freshly excreted urine and feces may reduce ammonia emissions from the animal house and therefore new concepts could be studied in proof of principle studies.
The separation of solid and liquid manure fractions after their mixed collection and the further processing of fractions is not primarily aiming at ammonia emission reduction. However the gaseous losses that are accompanied with these treatments should be monitored and only low emission technologies should be implemented.

Prospects and cost efficiency
Most separation and processing techniques are primarily aiming at better utilization of excreted minerals.
However the emission impacts of new manure treatment technologies should be evaluated in a manure chain approach.

Applicability and knowledge exchange between animal categories
Basic emission processes are the same in pig and cattle manure treatment systems. Because of different manure characteristics efficiency of separation will differ.

5.2 Manure application

Manure application in crops: wheat

Aim
Proof of principle overall ammonia losses when applying manure in wheat by analyses of field experiments carried out in recent years and international information

Background of research
Manure application in wheat becomes more common in the Netherlands, because manure application in autumn and early winter is not allowed any more on arable land on clay soils. Manure application in wheat crops should be carried out by shallow injection. To prevent crop damage, it is discussed whether the manure should be shallow-injected or that narrow band application should give sufficient emission reduction. Recently the first measurements on NH_3 volatilization after applying manure (shallow injection versus narrow band application) in a wheat crop in spring time were carried out.

Prospects and cost efficiency
Guidelines for manure application in wheat with best emission reducing effect.

Applicability
Methods for manure application are already implemented

Manure application in crops: potato and maize

Aim
Proof of principle low emission manure application in crops like potato and maize

Background of research
Manure application in crops will become more common due to the narrower time-windows for manure application. Manure application in crops (underneath a canopy) may become more applicable to manage manure application in terms of logistics. Currently new methods for manure application in crops, like potato and maize, are in development. These application techniques are mainly focussed on preventing crop-damage. To control ammonia emissions it is discussed how to effectively place or incorporate the manure between the potato ridges. Crop canopy may be a way to further reduce ammonia losses. In maize precise manure application in the crop row is an innovative option to better utilise manure (especially on sandy soils). This will lead to locally (the row) concentrated manure application and thus higher loads at a smaller area. Common application systems will need to be adapted to this row application within the constraint that ammonia emission needs to be controlled.

Prospects and cost efficiency
New application methods are being developed, but guidelines how to best control ammonia losses need to be made.

Applicability
New application techniques will become implemented due to the smaller time window for manure application. Parallel to this implementation good guidelines for emission reduction need to be underpinned.

Timing of manure application taking into account field and weather conditions

Aim
Proof of principle effects of manure application timing on ammonia losses

Background of research
Farm management by timing of manure application (emission reducing field and weather conditions) can help to control ammonia emissions. For a further reduction of ammonia volatilization following manure application on grassland and arable land next to the application methods also characteristics of the manure, soil and weather conditions during and after manure application should be taken into account to find the best emission reducing conditions. Taking into account these characteristics and conditions the present proved application techniques could be used more efficient in a way of achieving even more reduction of ammonia losses. To find the best conditions a model approach in combination with conducted measurements in the past seems to be the best method for the assessment of the best weather and soil conditions to control emissions after manure application. Currently, available models for this assessment are being reviewed.

Prospects and cost efficiency
Currently some experience is gathered with the timing of manure application. Good underpinned guidelines are still missing.

Applicability
Now how on the effects may in an easy way help farmers in their management of manure application.

High performance shallow injection, injection or incorporation on bare arable land

Aim
Optimize manure application on arable land to better control ammonia losses

Background of research
No emission factors are available for shallow injection on bare arable land. It is a proved application and it becomes more implemented in practice. It was recommended to start research on the emission factors for better assessment of the ammonia emission as this method is well implemented in common practice.
Direct incorporation of manure on arable land is prescribed since 2008. Direct incorporation can be achieved by 1. injection (direct deep placement) or 2. in one operation surface application and incorporation (the incorporation equipment is connected to the tank for the manure application); these two methods result in different emission factors. Optimization of the direct incorporation will help to further reduce ammonia losses.

Prospects and cost efficiency
Application techniques are proved and implemented. Assessment of ammonia emissions is necessary for optimization of use and more strict approval for reduction of ammonia losses.

Applicability
Well applicable as application methods are already on the market.

High performance manure application on grassland

Aim
Optimized manure application on grassland for better control of ammonia losses

Background of research
Since the introduction (and first measurements) of shallow injection on grassland in the early 90's a tendency was found of higher ammonia losses with this application technique over the following years. Changes in the technique or different use of the technique (for example higher application rates) may be the cause of these higher losses. A break of this trend or finding the causes to return to lower emissions will help to further decrease ammonia losses.
In the near future narrow band application on sandy soils will not be allowed any more, because a good alternative is available (shallow injection). Narrow band application in early spring time is in discussion as field conditions to make the band spreader pushing aside the grass are hardly met. Favoring/stimulating shallow injection on clay soils may help to further reduce ammonia losses. Conditions should be that way that soil and crop damage is prevented. Alternatives for peat soils may be considered.

Prospects and cost efficiency
Application techniques are proved and implemented. Assessment of ammonia emissions is necessary for optimization of use and more strict approval for reduction of ammonia losses.

Applicability and knowledge exchange between animal categories
Well applicable as application methods are already on the market.

Combination of emission reducing techniques

Aim
Combining best available techniques/methods to reduce ammonia emissions from field applied manure

Background of research
Next to the present applied application methods, increased reductions may be achieved by combinations of applications techniques and methods that interact with the process of ammonia volatilization; for instance by narrow band application or shallow injection of partly acidified manure (Huijsmans en Verwijs, 2008). The acidification may be carried out in the storage or batch wise just before application. The separate technologies are available for emission reduction but were never combined in a way to reach further reductions.

Prospects and cost efficiency
Technology is available but combination effects on ammonia reduction are not yet evaluated.

Applicability
Technology available; applicability depending on direct advantages for the farmer.

Treated manure

Aim
Proof of principle to determine the benefits (ammonia emissions) when applying treated manure

Background of research
Pilots have recently been started in the Netherlands to test the performance of different separation and further processing techniques, the crop mineral utilization and the environmental impacts. More treated,
(co-) digested or separated manures become available and recently research is started to use the treated manure as replacement of chemical fertilizer. Some treatments may lead to (specific) emission factors when applying that manure. Next to application rates (volume) and nutrient contents also the

manure characteristics (dry matter, viscosity) may affect the ammonia losses. Further developments in this area may have substantial effect on ammonia emissions after manure application.

Prospects and cost efficiency
Treated manure becomes available to handle and efficiently use and place the separate nutrients of manure. Effects on ammonia emissions are not yet known when applying these treated manures.

Applicability
Treatments are mainly carried out for efficient handling (transport) and utilization of nutrients. Little information is available about the (control of) ammonia emissions from field-applied treated manures.

Solid manure

Aim
Determine the ammonia emission from solid manures and the effectiveness of emission reduction methods

Background of research
Solid manure may be surface applied on grassland. On arable land the surface applied solid manure needs to be incorporated; the incorporation takes place some time after application; in that time emission takes place. For both solid manure application on grassland and arable land very little information is available on ammonia losses and on ways to reduce emissions.

Prospects and cost efficiency
Until now little attention is given to the emissions from solid manures. Field evaluation of the emission process and efficient application and incorporation methods may help to reduce ammonia emissions.

Applicability
Methods evaluated will be in line with optimization of nowadays application techniques.

5.3 Deposition

Aim
Screening the possibilities and quantitative impact of locally reducing the deposition of ammonia in vulnerable zones like Natura 2000 areas by implementing farm measures at close distances of these nature areas.

Measures that can be considered are:
a. changing the manure application management at a farm;
b. changing the geometry related characteristics of animal houses.

Considering manure application new appraoches have to be considered, like growing grass or crops or creating buffer zones depending on prevailing wind speeds and velocities. Considering the geometry of the housing the positioning of new-to-build farms regarding the vulnerable nature area's maybe relevant related to prevailing wind directions and wind speeds, the height of the outlet, the air velocity at the outlet and increasing effectivity of NH_3 reducing measures based on wind speed and -direction.

In a model approach the influence of the building geometry may be crucial. If a model approach of geometry related measures shows promising results, the building influences should be validated.

Background of research
This study is especially relevant to document and support the programmatic approach of nitrogen (PAS) at farm level and per NATURA 2000 area and to predict the progress that can be made by on farm deposition oriented measures.

Prospects and cost efficiency
A farm and region oriented approach is urgently needed both to make progress in reducing N deposition on nature areas and to define a future for farms nearby.

Applicability and knowledge exchange between animal categories
If this deposition approach shows promising results the option of incorporating such measures, probably including manure management in a user friendly tool like AAgrostacks should be considered. Such a tool then can be applied in planning and licensing permits for newly build or reorganizing farms.

Literature

Aarnink, A.J.A. & J. van Harn, 2010. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij; deskstudie naar mogelijke toevoegingen aan de oliefilm. Wageningen UR Livestock Research rapport 353, 12 pp

Aarnink, A.J.A., A.J. Van den Berg, A. Keen, P. Hoeksma and M.W.A. Verstegen, 1996. Effect of slatted floor area on ammonia emission and on the excretory and lying behaviour of growing pigs. Journal of agricultural engineering research 64, 299-310.

Aarnink, A.J.A., J.W. Schrama, M.J.W. Heetkamp, J. Stefanowska and T.T.T. Huynh, 2006. Temperature and body weight affect fouling of pig pens. Journal of animal science 84, 2224-2231.

Aarnink, A.J.A., J. Huis in 't Veld, A. Hol, I. Vermeij, 2007[a]. Kempfarm vleesvarkensstal: milieu-emissies en investeringskosten. ASG Rapport 67, 32 pp

Aarnink, A.J.A., Ellen, H.E., Huijsmans, J.F.M., Smits, M.C.J. & D.A.J. Starmans, 2007[b]. Emission abatement in practical situations. In: Ammonia, the case of The Netherlands, Wageningen Academic Publishers, p 69-102.

Aarnink, A. J. A., J. M. G. Hol, en G. M. Nijeboer. 2008[a]. Ammonia emission factor for using benzoic acid (1% vevovitall) in the diet of growing-finishing pigs., Animal Sciences Group, Divisie Veehouderij, Lelystad.

Aarnink, A.J.A., J. van Harn, T.G. van Hattum, Y. Zhao, J.W. Snoek, I. Vermeij and J. Mosquera, 2008[b]. Reductie stofemissie bij vleeskuikens door aanbrengen oliefilm. Rapport 154, Animal Sciences Group, Wageningen University and Research Centre. 42 p.

Aarts, H.F.M., Hilhorst, G.J., Sebek, L.B.J., Smits, M.C.J., Oenema, J., 2007. De ammoniakemissie van de Nederlandse melkveehouderij bij een management gelijk aan dat van deelnemers aan "Koeien & Kansen*".* Wageningen : Wettelijke Onderzoekstaken Natuur & Milieu, Rapport / Wettelijke Onderzoekstaken Natuur & Milieu I 63, 46 pp

Asman, W.A.H., 2008. Entrapment of ammonia, odor compounds, pesticide sprays and pathogens by shelterbelts. DJF Plant Science Report No. 135, Faculty of Agricultural Sciences, University of Aarhus, Denmark, 167 pp.

Baltussen, W.H.M., C.J.A.M. de Bont, A. van den Ham, P.L.M. van Horne, R. Hoste en H.H. Luesink (2010a) Gevolgen van het afschaffen van dierrechten. Den Haag, LEI, 2010, Rapport 2010-048

Baltussen, W.H.M., R. Hoste, H.B. van der Veen, s.Bokma, P. Bens en H. Zeewuster (2010b) Economische gevolgen van bestaande regelgeving voor de Nederlandse Veehouderij. LEI, Wageningen UR, Den Haag, rapport 2010-010.

Bakker, G.C.M. & M.C.J. Smits. 2002. Dietary factors are additive in reducing in vitro ammonia emissions from pig manure. *Journal of Animal Science.* 79 (Supplement 1): Suppl. 1, 753 Abstr.

Beheerplan Natura 2000 Peelgebieden, 2010. http://www.natura2000beheerplannen.nl/files/peelspecial-naturanieuwsbrief-juni-2010.pdf

Braam, C.R., Smits, M.C.J., Gunnink, H. and Swierstra D. 1997(a). Ammonia Emission from a Double-Sloped Solid Floor in a Cubicle House for Dairy Cows. Journal of Agricultural Engineering Research 68, 375-386.

Braam, C.R., Ketelaars, J. and Smits, M.C.J., 1997(b). Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. Netherlands Journal of Agricultural Science 45: 49-64

Bussink, D.W., 1996. Ammonia volatilization from intensively managed dairy pastures. PhD-thesis, Agricultural University Wageningen, Netherlands, 177 p.

Bussink, D.W., J.F.M. Huijsmans & J.J.M.H. Ketelaars, 1994. Ammonia volatilization from nitric-acid-treated cattle slurry, (surface) applied to grassland. Netherlands Journal of Agricultural Science 42: 293-309.

Cambra-López, M., Winkel, A., Harn, J. van, Hannink, N., Aarnink, A.J.A., 2009. Measures to reduce fine dust emission from poultry houses: reduction from broiler houses by ionization. ASG Report 215, Lelystad, Netherlands, 41 pp.

Canh T.T., Aarnink A.J.A., Mroz Z., Jongbloed A.W., Schrama J.W. & Verstegen M.W.A., 1998[a]. Influences of electrolyte balance and acidifying calcium salts in the diet of growing-finishing pigs on urinary pH, slurry pH and ammonia volatilisation from slurry. Livestock Production Science 56, 1–13.

Canh T.T., Aarnink A.J.A., Schutte J.B., Sutton A., Langhout D.J. & Verstegen M.W.A., 1998[b]. Dietary protein affects nitrogen excretion and ammonia emission from slurry of growing–finishing pigs. Livestock Production Science 56, 181–191.

Canh T.T., Aarnink A.J.A., Verstegen M.W.A. & Schrama J.W., 1998[c]. Influences of dietary factors on the pH and ammonia emissions of slurry from growing–finishing pigs. Journal of Animal Science 76, 1123–1130.

Canh T.T., Sutton A.L., Aarnink A.J.A., Verstegen M.W.A., Schrama J.W. & Bakker G.C.M., 1998[d]. Dietary carbohydrates alter faecal composition and pH and ammonia emission from slurry of growing pigs. Journal of Animal Science 76, 1887–1895.

Canh T.T., Verstegen M.W.A., Aarnink A.J.A. & Schrama J.W., 1997. Influence of dietary factors on nitrogen portioning and composition of urine and faeces of fattening pigs. Journal of Animal Science 75, 700–706.

Celen, M. F., S. Kozat, S. Ekin, B. H. Yoruk, and E. Alki. 2008. Effects of adding aluminum sulfate to different litters on selected trace elements and vitamins concentrations in broiler. African Journal of Biotechnology 7: 3363-3366.

Chardon, W.J., J. Van Der Molen & H.G. Van Faassen, 1991. Modelling ammonia emissions from arable land. In: V.C. Nielsen, J.H. Voorburg & P. L'Hermite (Eds.), Odor and ammonia emissions from livestock farming, Proceedings of a seminar, Silsoe, United Kingdom, 26-28 March 1990. Elsevier applied science, Londen and New York, pp. 156-165.

Corré, W.J., 2006. Beweiding en nitraatuitspoeling : praktijkgegevens en experimenten Wageningen : Plant Research International,, Rapport Plant Research International 110.

Costa, A. en M. Guarino. 2008. Photocatalytic TiO_2 treatment effects on ammonia, greenhouse gases, dust concentration and emission in a weaning room. AgEng 2008.

De Haan B.J., Dam J.D. van, Willems W.J., Schijndel M.W. van, Sluis S.M. van, Born G.J. van, Grinsven J.J.M. van, 2009. Emissiearm bemesten geëvalueerd. PBL-publicatienummer 500155001, Bilthoven

Derikx, P.J.L., and A.J.A. Aarnink. 1993. Reduction of ammonia emission from slurry by application of liquid top layers. In: M.W.A. Verstegen, L. A. Den Hartog, G.J.M. van Kempen, and J.H.M. Metz (Ed.) Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publ. No. 69. p 344. Pudoc, Wageningen, The Netherlands.

Derikx, P.J.L., A.J.A. Aarnink, P. Hoeksma & H.C. Willers, 1995. Vermindering van ammoniakemissie uit mest door een vloeibare afdeklaag. IMAG rapport

Dijk, C.J. van, Th.A. Dueck, G.W.W. Wamelink en J. Mosquera. 2005. Invloed van een landschapselement (windsingel) op de verspreiding van ammoniak uit een varkenshouderij. Nota 333, Plant Research International B.V., Wageningen.

Dooren H.J.C. van & P.J. Galama, 2009. Internationale verkenning van ervaringen met vrijloopstallen. ASG Rapport 244, 25 pp

Doppenberg, J. and van der Aar, P. (Eds.), 2007. Biofuels: implications for the feed industry. Wageningen Academic Publishers, Wageningen..

Duinkerken, G. van, M.C.J. Smits, G. André, L.B.J. Šebek and J. Dijkstra, 2009. Milk urea concentration as an indicator of ammonia emission from dairy cow houses in a situation with restricted grazing. Submitted to J. Dairy Science

Ellen, H.H., J. van Harn, T. Veldkamp. Juni 2005. Inventarisatie mogelijkheden reductie ammoniakemissie uit vleeskuikenstallen. Animal Sciences Group PraktijkRapport Pluimvee 16

Ellen, H.H., J.M.G. Hol, A.I.J. Hoofs, J. Mosquera, A.J.J. Bosma, 2008[a]. Ammoniakemissie en kosten van chemische luchtwasser met bypassventilatoren bij vleesvarkens Ammonia emission and costs of a chemical air scrubber with bypass ventilation at a pig house. Wageningen UR Animal Sciences Group Rapport 151, 26 pp

Ellen, H.H.; Rijn, D. van; Smeets, J.H., 2008[b]. Energiebesparing met alternatieve verwarmingssystemen in de vleeskuikenhouderij. Animal Sciences Group Rapport 130, 35 pp

FAO, 2009. The State of Food and Agriculture. Towards a Responsible Livestock Future. Rome (in press).

French, P., L. Boyle, J. Hourihan, C. Augestenborg and K. O Driscoll, 2008. Development of Sustainable low cost animal accommodation (Out wintering pads (OWP's)). End of Project Report Project 5232, Moorepark Dairy Production Research Centre, Fermoy, Co. Cork, Ireland, 47 pp www.teagasc.ie/research/reports/dairyproduction/5232/eopr-5232.pdf

Freney, J.R., J.R. Simpson & O.T. Denmead, 1983. Volatilization of ammonia. In: J.R. Freney & J.R. Simpson (Eds.), Gaseous loss of nitrogen from plant-soil systems. Martinus Nijhoff/Dr. W. Junk, The Hague, pp. 1-31.
Géneremont, S, & P. Cellier, 1997. A mechanistic model for estimating ammonia volatilization from slurry applied to bare soil. Agricultural and Forest Meteorology 88: 145-167
Goudappel-Coffeng. (2010) Ministerie van Landbouw, Natuur en Voedselveiligheid; PAS- rekentool. Draft versie 2, 21 pp
Groenestein, C.M., Huijsmans, J.F.M., Schils, R.L.M., 2010. Emissies van broeikasgassen, ammoniak, fijn stof en geur in de mestketen. Wageningen UR Livestock Research Rapport, 28 pp
Groot koerkamp, P.W.G., 1998. Ammonia emission from aviary housings systems for laying hens. PhD thesis, Wageningen University, 161 pp
Groot Koerkamp, P.W.G. & Groenestein, C.M. (2008). Ammonia and odor emission from a broiler house with a litter drying ventilation system. In: AgEng2008 Agricultural and Biosystems Engineering for a Sustainable World.
Guarino, M., A. Costa, D. Berckmans. 2007. A new low cost technique to reduce concentration pollutants in animal houses. Dustconf2007, Maastricht
Hacker, R.R., J.R. Ogilvie, W.D. Morrison and F. Kains, 1994. Factors affecting excretory behavior of pigs. Journal of Animal Science 72, 1455-1460.
Harn, J. van; Mosquera Losada, J.; Aarnink, A.J.A., 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij; Invloed strooiselmateriaal op fijnstof- en ammoniakemissie uit vleeskuikenstallen. Wageningen UR, Animal Sciences Group Rapport 218, Lelystad, 34 p
Hofschreuder, P., 2010. Notitie ammoniakdepositie en afstand tot de stal. Notitie in opdracht van LNV, 9 pp.
Hofschreuder, P., 2008. Vegetative shelterbelts close to livestock houses to improve air quality: a quick scan *Lelystad : Animal Sciences Group,in Dutch,* Animal Sciences Group Rapport 136, 15 pp
Hofschreuder, P, Willers, H..C, Ogink, N.W., 2005. Geurhinder en geurbeleving; Een vergelijking tussen de afstandstabel en berekeningen met het Nieuw Nationaal Model.A&F report 551 47 pp
Hol, J.M.G. and I.H.G. Satter, 1998. Praktijkonderzoek naar de ammoniakemissie van stallen XIX. Vleesvarkensstal met gereduceerd emitterend oppervlak door aangepaste hokinrichting. DLO Report 98-1001. IMAG, Wageningen, the Netherlands.
Huijsmans, J.F.M., E.M. Mulder & D.W. Bussink, 1994. Acidification of slurry just before field application to reduce ammonia emission. International Conference on Agricultural Engineering, Milano, 29th August - 1st September 1994, p. 4-5.
Huijsmans, J.F.M., J.M.G. Hol & M.M.W.B. Hendriks, 1997. Ammoniakemissie na toediening van verdunde mest. Het effect van de verdunning van mest en andere factoren op de ammoniakemissie na bovengrondse breedwerpige mesttoediening. IMAG-DLO rapport P 97-75, pp. 13.
Huijsmans, J.F.M., J.G.L. Hendriks & G.D. Vermeulen, 1998. Draught requirement of trailing-foot and shallow injection equipment for applying slurry to grassland. *Journal of Agricultural Engineering Research* 71: 347-356.
Huijsmans, J.F.M. & R.M. De Mol, 1999. A model for ammonia volatilization after surface application and subsequent incorporation of manure on arable land. *Journal of Agricultural Engineering Research* 74: 73-82.
Huijsmans, J.F.M., J.M.G. Hol & M.M.W.B. Hendriks, 2001. Effect of application technique, manure characteristics, weather and field conditions on ammonia volatilization from manure applied to grassland. Netherlands Journal of Agricultural Science 49: 323-342.
Huijsmans, J.F.M. 2003. Manure application and ammonia volatilization. PhD thesis Wageningen University with summaries in English and Dutch, Wageningen, The Netherlands, ISBN 90-5808-937-1, pp 160.
Huijsmans, J.F.M., J.M.G. Hol & G.D. Vermeulen, 2003. Effect of application method, manure characteristiscs, atmosphere and field conditions on ammonia volatilization from manure applied to arable land. Atmospheric Environment 37: 3669-3680.
Huijsmans, J..F.M. and J. Mosquera, 2007. Ammoniakemissies bij het uitrijden van verwerkte mest, deskstudie. Plant Research International, Wageningen, report 156, pp. 20.
Huijsmans, J..F.M., J. Mosquera and J.M.G. Hol, 2007. Ammoniakemissies bij het uitrijden van vaste mest, deskstudie. Plant Research International, Wageningen, report 155, pp. 20.

Huijsmans, J.F.M. and B. Verwijs, 2008. Ammoniakemissie bij alternatieve mesttoedieningsmethoden. Plant Research International, Wageningen, report 220, pp. 26.
Huijsmans, J.F.M. and G.D. Vermeulen. Emissiefactoren uitrijden direlijke mest. Notitie werkgroep ammoniak.

Huynh, T.T.T., A.J.A. Aarnink, H.A.M. Spoolder, B. Kemp and M.W.A. Verstegen, 2004. Effects of floor cooling during high ambient temperatures on the lying behavior and productivity of growing finishing pigs. Transactions of the ASAE 47 (5), 1773-1782.
Janssen, L.H.J.M., V.R. Okker and J. Schuur. 2006. Welvaart en Leefomgeving. Een scenariostudie voor Nederland in 2040. Centraal Planbureau, Milieu- en Natuurplanbureau and Ruimtelijk Planbureau, 239 pp.
Kai, P., P. Pedersen, J. E. Jensen, M. N. Hansen, and S. G. Sommer. 2008. A whole farm assessment of the efficacy of slurry acidification in reducing ammonia emissions. European Journal of Agronomy 28: 148.
Kema, 2007. Rekenen met AAgro-Stacks. Handleiding voor het model. Pp 19.
Melse, R.W.& Ogink, N.W.M., 2004. Toepassing van luchtbehandelingstechnieken binnen de intensieve veehouderij. Fase 2: Mogelijkheden tot kostenverlaging van wassers. Agrotechnology & Food Innovations rapport 271, 58 pp
Melse, R.W.; Wagenberg, A.V. van; Mosquera, J., 2006. Size reduction of ammonia scrubbers for pig and poultry houses: Use of conditional bypass vent at high air loading rates Biosystems Engineering 95 (1): 69 - 82.
Melse, R.W.; Ogink, N.W.M.; Rulkens, W.H., 2009. Air treatment techniques for abatement of emissions from intensive livestock production. The Open Agriculture Journal 3: 6 – 12
Menard, J.L. & Y Seité, 2009. Parc stabiles d'hivernage, conception et fonctionnement. Cap élevage 40: 30-31.
Milieubalans, 2009. www.pbl.nl/nl/publicaties/2009/milieubalans
Mitchell, B.W., J. Richardson, J. Wilson, C. Hofacre. 2004. Application Of An Electrostatic Space Charge System For Dust, Ammonia And Pathogen Reduction In A Broiler Breeder House. Applied Engineering in Agriculture v.20 p.87-93 2004.
Mooney, H., H. Steinfeld, F. Schneider, L. Neville. 2009. Livestock in a Changing Landscape. Drivers, Consequences and Responses. Island Press, (in press)
Moore, P. A., T. C. Daniel, D. R. Edwards, and D. M. Miller. 1995. Effect of chemical amendments on ammonia volatilization from poultry litter. Journal of Environmental Quality 24: 293-300.
Monteny, G.J., 2000. Modelling of ammonia emissions from dairy cow houses. Thesis Wageningen University, Wageningen, the Netherlands, 155 p.
Monteny, G.J., J. Huis in 't Veld, G. Van Duinkerken, G. André, and F. Van der Schans. 2001. Naar een jaarrond emissie van ammoniak uit melkveestallen.IMAG Rapport 2001-09. IMAG, PV and CLM, Wageningen, the Netherlands.
Oenema, O., T.V. Vellinga and H. van Keulen, 2006.. Nutrient management under grazing. Pp 63-83 In: S. Tamminga, J. Dijkstra and A. Elgersma (eds.) Fresh herbage: the key to a sustainable food chain. Springer, Dortrecht, Netherlands. 194 pp.
Oenema, O., J.W.H. van der Kolk en A.M. Groot, 2006. Landbouw en Milieu in Transitie WOT-studies, Wageningen, 106 pp. Oenema, O., D.A. Oudendag and G.L. Velthof 2007. Nutrient losses from manure management in the European Union. Livestock Science 112 261–272
Oenema, O., D.A. Oudendag and G. L.Velthof, 2007. Changes in livestock production in the European Union; Driving forces, manure management and nutrient losses. Pp. 39-82. In: Serie Simposios Y Compendios Volumen 12 y 13. Sociedad Chilena de Produccion Animal. Sochipa A.G.
Oenema, O. 2007. Transitions in agriculture in The Netherlands 1850-2030: Towards a healthy and durable production. Pp 125-148. In: Starmans, D.J.A. and K.W. van der Hoek (Eds) Ammonia, The case of The Netherlands. Wageningen Academic Publishers, Wageningen, 201 pp.
Oenema, O., D.A. Oudendag, H.P. Witzke, G.J. Monteny, G.L.Velthof, S. Pietrzak, M. Pinto, W. Britz, E. Schwaiger, J.W. Erisman, W. de Vries, J.J.M. van Grinsven & M. Sutton, 2007. Integrated measures in agriculture to reduce ammonia emissions; final summary report. Alterra, 186 pp, http://www.scammonia.wur.nl).
Oenema, O. and G.L. Velthof 2007. Analysis of International and European Policy Instruments: Pollution Swapping. Ammonia Service Contract 070501/2005/422822/MAR/C1, Task 2. Alterra Report. Wageningen, ., http://www.scammonia.wur.nl).

Oenema, O., A. Bannink, S.G. Sommer, J.W. Van Groenigen, and G.L. Velthof. 2008. Gaseous Nitrogen Emissions from Livestock Farming Systems. In: R.F. Follett and J.L. Hatfield, Eds) Nitrogen in the Environment: Sources, Problems, and Management. Elsevier. P. 395-441.
Oosterbaan, A.; Tonneijck, A.E.G.; Vries, E.A. de, 2006.. Kleine landschapselementen als invangers van fijn stof en ammoniak. Wageningen : Alterra-rapport 1419.
Patterson, P.H. en Adrizal. 2005. Management Strategies to Reduce Air Emissions: Emphasis - Dust and Ammonia. Journal of Applied Poultry Research, 2005, 14:638-650.
Projectgroep Revisie Nationaal Model. (1998) Het Nieuwe nationaal Model; Model voor de verspreiding van luchtverontreiniging uit bronnen over korte afstanden. TNO-MEP pp292. (te bestellen als ISBN 90-76323-00-3 bij Infomil.
Rav, 2010. Regeling Ammoniak en veehouderij. Staatscourant nr 9996, 29 juni 2010. Den Haag, NL
Reijs, J., 2007. Improving slurry by diet adjustments, PhD thesis, Wageningen University.
Van der Stelt, B, 2007. Chemical characterization of manure in relation to nitrogen emissions to the environment. PhD thesis, Wageningen University.
Reitsma, B. and C.M. Groenestein, 1995. Praktijkonderzoek naar de ammoniakemissie van stallen XIX. Hellingstal voor vleesvarkens. DLO Report 95-1002. DLO, Wageningen, the Netherlands.
Ritz, C.W., B.W. Mitchell, B.D. Fairchild, M. Czarick and J.W. Worley. 2006. Improving In-House Air Quality in Broiler Production Facilities Using an Electrostatic Space Charge System. Journal of Applied Poultry Research, 2006, 15:333-340.
Silvis, H.J., C.J.A.M. de Bont, J.F.M. Helming, M.G.A. van Leeuwen, F. Bunte en J.C.M van Meijl, 2009. De agrarische sector in Nederland naar 2020; Perspectieven en onzekerheden. LEI-Rapport 2009-021
Schröder, J.J.; Aarts, H.F.M.; Middelkoop, J.C. van; Haan, M.H.A. de; Schils, R.L.M.; Velthof, G.L.; Fraters, B.; Willems, W.J., 2007. Permissible manure and fertilizer use in dairy farming systems on sandy soils in The Netherlands to comply with the Nitrates Directive target. European Journal of Agronomy 27 . - p. 102 - 114.
Sleurink, D. 2001. 'Het werkt …maar de techniek is niet klaar.' Pluimveehouderij, jaargang 31, nr 13, pag. 14-15
Smits, M.C.J., 1998. Grooving a solid V-shaped floor; some observations on walking behaviour and ammonia emission, in Dutch.. IMAG Report P 98-60. IMAG-DLO, Wageningen, the Netherlands.
Smits, M.C.J.; Bokma, S., 2008. Verkenning perspectief van ureaseremmers voor beperking van ammoniakemissie uit Nederlandse melkveestallen. Lelystad : Animal Sciences Group, Report 141
Smits, M.C.J.; Campen, J.B.; Huis in 't Veld, J.W.H., 2008. Emission reduction by slurry pit air separation in a veal calf house; proof of principle Lelystad : Animal Sciences Group report 179
Smits, M.C.J, A.J.J. Bosma, J.P.M. Ploegaert & P.Hofschreuder, 2010. Reductie geurbelasting varkensstallen; verkenning van technische mogelijkheden, kosten en verspreidingsberekeningen. Wageningen UR Livestock Research Rapport 388, 28 pp
Søgaard, H.T., S.G. Sommer, N.J. Hutchings, J.F.M. Huijsmans, D.W. Bussink & F. Nicholson, 2002. Ammonia volatilization from field-applied animal manure-the ALFAM model. Atmospheric Environment 36: 3309-3319.
Sommer S.G., Oenema O., Chadwick D., Misselbrook, Harrison R., Hutchings N.J., Menzi H., Monteny G.-J., Ni, J.-Q. and Webb J., 2006. Algorithms determining ammonia emission from buildings housing cattle and pigs and from manure stores. Agronomy Journal 89: 264-335.
Starmans, D.A.J. & K.W. van der Hoek, 2007. Ammonia, the case of The Netherlands, Wageningen Academic Publishers, 201 pp.
Starmans, D. & N. Ogink. 2008. Note on the feasibility of TiO_2 as a catalyst to reduce ammonia on a large scale in commercial farms. ASG Livestock production (in Dutch), Wageningen.
Steinfeld, H., P. Gerber, T. Wassenaar, V. Castel, M. Rosales, and C. de Haan. 2006. Livestock's long shadow: environmental issues and options. Rome: Food and Agriculture Organization.
Steinfeld, H. Moony & H.A., F. Schneider And L. Neville, 2010. Livestock in a changing landscape, volume 1: drivers, consequences and responses. Island Press, USA 864 pp
Swierstra, D., C.R. Braam, & M.C.J. Smits, 2001. Grooved floor systems for cattle housing: ammonia emission reduction and good slip resistance. Applied Engineering in Agriculture17 (1): 85-90
Tamminga, S., Oenema, O. & A. Aarnink, 2009. Livestock feeding strategies. In: UNECE Guidance document for preventing and abating ammonia emissions from agricultural sources. In preparation.

Taskforce Stikstof/ammoniak i.r.t. Natura 2000, 2008. Een verkenning van oplossingsrichtingen. Rapport van een taskforce onder voorzitterschap van de heer C. Trojan in opdracht van de Minister van Landbouw, natuur en voedselkwaliteit. 30 juni 2008, 48 pp

Valk, H., 2002. Nitrogen and phosphorus supply of dairy cows. PhD thesis, Utrecht University, 204 pp

Van der Stelt, B., 2007. Chemical characterization of manure in relation to nitrogen emissions to the environment. PhD thesis, Wageningen University.

Van Pul, W.A.J., Jaarsveld, J.A. van, Vellinga, O.S., Broek, M. van den & M.C.J. Smits, 2008. The VELD experiment: An evaluation of the ammonia emissions and concentrations in an agricultural area. Atmospheric Environment 42 (34). - p. 8086 - 8095.

Vrolijk, H., J. Helming, H. Luesink, P.W. Blokland. D. Oudendag, M. Hoogeveen, H. van Oostenbrugge en J. Smit. 2008. Nationale Emissieplafonds 2020. Impact of de Nederlandse Landbouw en Visserij. Rapport 2008-069. LEI, Den Haag, 158 pp.

Vuuren, A.M. van, 1993. Digestion and nitrogen metabolism of grass fed dairy cows. Wageningen Agricultural University NL, 134 pp.

Vuuren, A.M. van; Pol-van Dasselaar, A. van den, 2006. Grazing systems and feed supplementation. In: Fresh Herbage for Dairy Cattle: the Key to a Sustainable Food Chain / Elgersma, A., Dordrecht: Springer, Wageningen UR Frontis series 18.

Wichink Kruit, R.J. (2010) Surface-atmosphere exchange of ammonia; Measurements and modeling over non-fertilized grassland in the Netherlands. Dissertation WUR Meteorology and Air Quality. Pp 175.

Winkel, A., M. Cambra-López, J. van Harn, T.G. van Hattum en A.J.A. Aarnink, 2009. Maatregelen ter vermindering van fijnstofemissie uit de pluimveehouderij: optimalisatie van een oliefilmsysteem bij vleeskuikens. ASG Rapport 204, Lelystad, Netherlands, 44 pp

Zanten, M. van, Sauter, F, Wichink Kruit, R, Jaarsveld, H. van, Pul, A van., 2010. Description of the DEPAC module; Dry deposition modelling with DEPAC_GCN2010. Concept,. 50 pp.

Wageningen UR Livestock Research

Edelhertweg 15, 8219 PH Lelystad T 0320 238238 F 0320 238050

E info.livestockresearch@wur.nl I www.livestockresearch.wur.nl