Strategies to reduce losses and improve utilisation of nitrogen from solid cattle manure

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This dissertation is dedicated to
my beloved parents

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Chapter 1

General introduction

Ghulam Mustafa Shah

1.1. Background and introduction of the problem

Nitrogen (N) is a vital element for crop and livestock production. While the crop takes up N from the soil via roots and some from the air via stomata in leaves, N intake by livestock is via animal feed. Of the consumed feedstuffs by livestock, between 5 and 45% of the N is retained or secreted in meat, milk and eggs, whereas the remainder is excreted out of the body in urine and faeces (Fig. 1.1). Hence, between 55 and 95% of the N content of ingested feed by farm animals is excreted in manure. Consequently, livestock manure is a valuable source of N for the soil-crop system. However, significant N losses may occur from the manure management chain (i.e. housing, storage and field application), which not only pollute the environment but also reduce its N fertiliser value. The challenge is to efficiently manage the manure in order to improve on-farm N cycling within the livestock-manure-soil-crop continuum (Fig. 1.1).

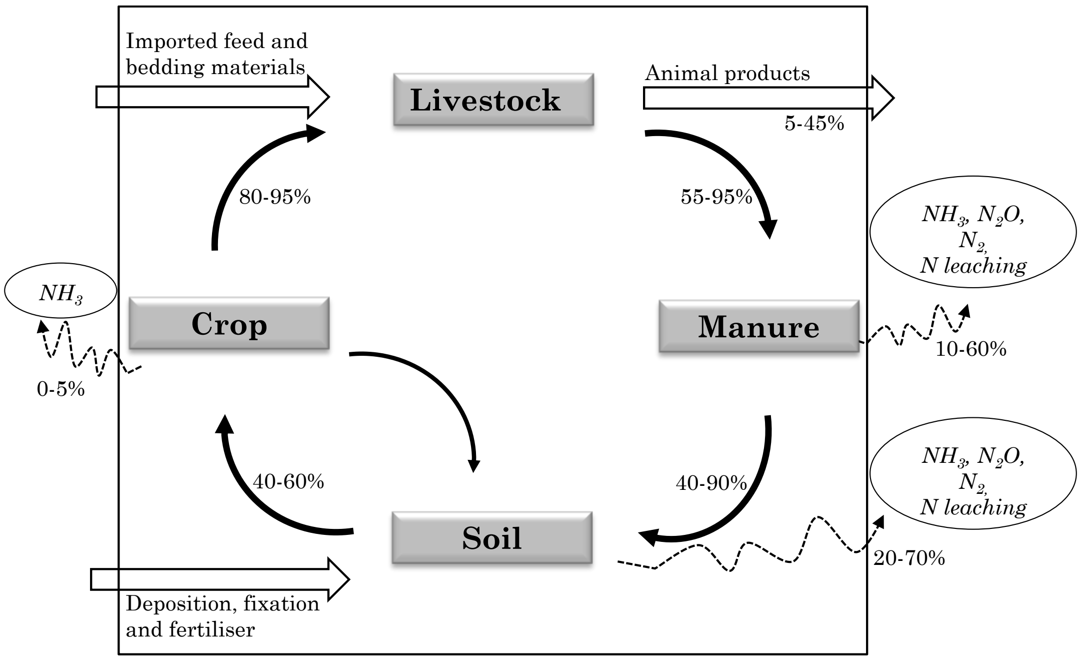

Fig. 1.1. Flow chart of the N cycle in livestock-based farming systems with four N pools, i.e. livestock, manure, soil and crop. Percentages indicate the range of estimated N transfer from one pool to another pool and N losses from each pool of the system (Sources: Haas et al. 2002; Oenema and Tamminga 2005).

1.2. Solid cattle manure management--a global perspective

Cattle are by far the largest producer of livestock manure N in the world, because of their large number and relatively large manure excretion rates (Sheldrick et al. 2003). The urine and faeces dropped by grazing cattle is left unmanaged in pastures, but the urine and faeces of confined and housed cattle is collected together with bedding materials and managed depending on the housing systems. In many parts of Africa and Asia, cattle are typically housed on earth or concrete floors, sometimes with rice or wheat straw as bedding material. Thus the manure produced is a solid mixture of faeces, some urine, bedding material and spoiled feed. In Asia, solid manure produced by cattle is regularly scrapped off the floor and composted before its use as plant fertiliser and for soil amelioration, and/or air-dried before using it as bedding material and energy source (cooking). In Africa, the manure is often a scarce resource and is considered as a main source of concentrating nutrients within farming systems (Rufino et al. 2007). Agriculture in Africa and much of Asia is dominated by resource poor small-holder farms, thus the importance of controlling losses from manure there is associated with sustainability rather than pollution problems.

In America and Europe, cattle are predominantly housed in cubicle barns producing slurry manure (Petersen et al. 2007). However, the proportion of solid cattle manure is increasing in some parts due to the renewed interest in straw-based housing systems for better animal health (less claw and back problems) and welfare (more comfort) (Ellen et al. 2007). In North America, almost all the solid cattle manure collected from the open feedlots is composted and used as soil conditioner and fertiliser (Miller and Berry 2005; Larney et al. 2006). In a comparative study in Denmark, Hutchings et al. (2001) concluded that total ammonia (NH_3) emissions from the solid manure management chain (litter barn, open storage and field application) are roughly two times higher (~35 vs. ~18% of the excreted N) than in case of the slurry management chain. The contribution of these emissions to environmental pollution has become a major social and political concern in the developed world, especially in Western Europe (Van der Meer et al. 1987).

Emission to air and water bodies from cattle manure is unavoidable to a certain extent (Petersen et al. 2007). These emissions arise from biological, chemical and physical processes involved in degradation of manure immediately after its excretion in the barn, during storage and after field application. Of particular importance are methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O) and NH_3 emissions to the atmosphere, and N and phosphorus (P) leaching losses (including runoff and erosion) to surface waters and groundwater (Tamminga 1992; Oenema et al. 2001). Leaching of N and P deteriorates the water quality and causes eutrophication. Further, this can change the ecological functioning of surface waters. Potential consequences associated with NH_3 emission include (i) contribution to acidification and eutrophication in ecosystems (Pearson and Stewart 1993), (ii) loss of biodiversity and (iii) respiratory diseases caused by the exposure to the fine particulate matter (Ndegwa et al. 2008). The N_2O and CH_4 emissions may contribute to global warming and N_2O has recently been recognised as the dominant ozone-depleting substance (Ravishankara et al. 2009).

To restrict the increase in environmental pollution from animal manure, a series of governmental policy measures have been implemented in a number of countries and especially the European Union (Oenema et al. 2011). In view of the objectives of these policy measures and in particular the emission ceiling (target) for 2020 of the national emission ceiling directive (NECD; Annonymous 2001), there is a great need to identify and develop efficient manure management practices that will assist farmers in reducing N losses. This is not only to enable NECD to meet the regulatory requirements but also to increase farm profitability by maximising manure N utilisation. To this end, several practices have been examined for solid cattle manure management. These include the use of additional straw (Gilhespy et al. 2009) and frequent removal of manure from the barn (Ndegwa et al. 2008). However, the solid cattle manure management after collection from the barn has always been a challenge for the farmers.

1.3. Manure storage

After excretion in the barn, solid cattle manure is either directly applied to the field and/or stockpiled or composted in the open air for an extended period of time prior to land application. In the solid manure management chain, the storage phase is critical since up to about 50% of the initial total carbon (C) and N can be lost during this step (Kirchmann 1985; Eghball et al. 1997; Larney et al. 2006). Attempts have been and are being made in developing effective techniques to reduce these storage losses. During the late 19^{th} century, several chemical conservation methods of N have been tested by mixing the fresh manure with calcium sulphate, elemental sulphur, quick lime, potassium salts and phosphates (Krause 1890; Dietzell 1897 cited in Kirchmann 1985). Except a slight reduction in N losses by superphosphate the above-mentioned additives were not effective. Besides, straw litter and peat were used because of their high absorption capacity for urine (Virri 1941 cited in Kirchmann 1985). However, due to the greater excretion of N by cows (up to 250 g N $cow^{-1}day^{-1}$), the worthwhile conservation of N through the moderate amount of tested inorganic chemicals and peat was not possible (Kirchmann 1985).

In addition, effectiveness of various storage conditions on N losses was tested. For this purpose, three main storage conditions were distinguished: (i) anaerobic decomposition, (ii) anaerobic-aerobic decomposition and (iii) aerobic decomposition or composting (Kirchmann 1985). Especially storing manure anaerobically by tightly packing in pits or manure houses was found to be effective with only 5-20% N loss during a period of 3 to 7 months (Hansen 1928; Siegel and Meyer 1938; Rauhe and Koepke 1967). Chadwick (2005) found that NH_3 emission during storage of cattle farmyard manure could be restricted by 50 to 90% through compaction followed by covering the heaps with a plastic sheet. Sagoo et al. (2007) demonstrated that covering broiler litter with a plastic sheet reduced total N losses during storage by ca, 70% and NH_3 emission by ca, 90% compared to conventionally stockpiled manure heaps. Some farmers stockpile solid cattle manure in a roofed building with the aim to protect it against precipitation and therefore to reduce especially leaching losses (Mosquera et al. 2006). Despite all these efforts, there are still large uncertainties in the emission estimates from the basket of storage methods whilst the routes of N loss are also not well quantified yet.

1.4. Manure application

1.4.1. Gaseous N losses

Land application of manure is a critical step in manure management as it is one of the major sources of NH_3 emission into the air (Hutchings et al. 2001). Huijsmans et al. (2007) concluded that NH_3 emission after application of solid cattle manure to grassland can be up to 100% of the total ammoniacal N (TAN) content. Various factors can affect the emission of NH_3 from manure into the environment. According to Sommer and Hutchings (2001) these are categorised into four groups: manure characteristics, application management, soil conditions and environmental factors (Fig. 1.2).

The NH_3 concentration at the liquid surface is primarily a function of the chemical and physical conditions within the manure, whereas the transfer of NH_3 from the manure surface to the atmosphere is primarily a function of the local meteorological conditions. Consequently, minimising the area and time of exposure of manure N to the atmosphere could be a good option to reduce NH_3

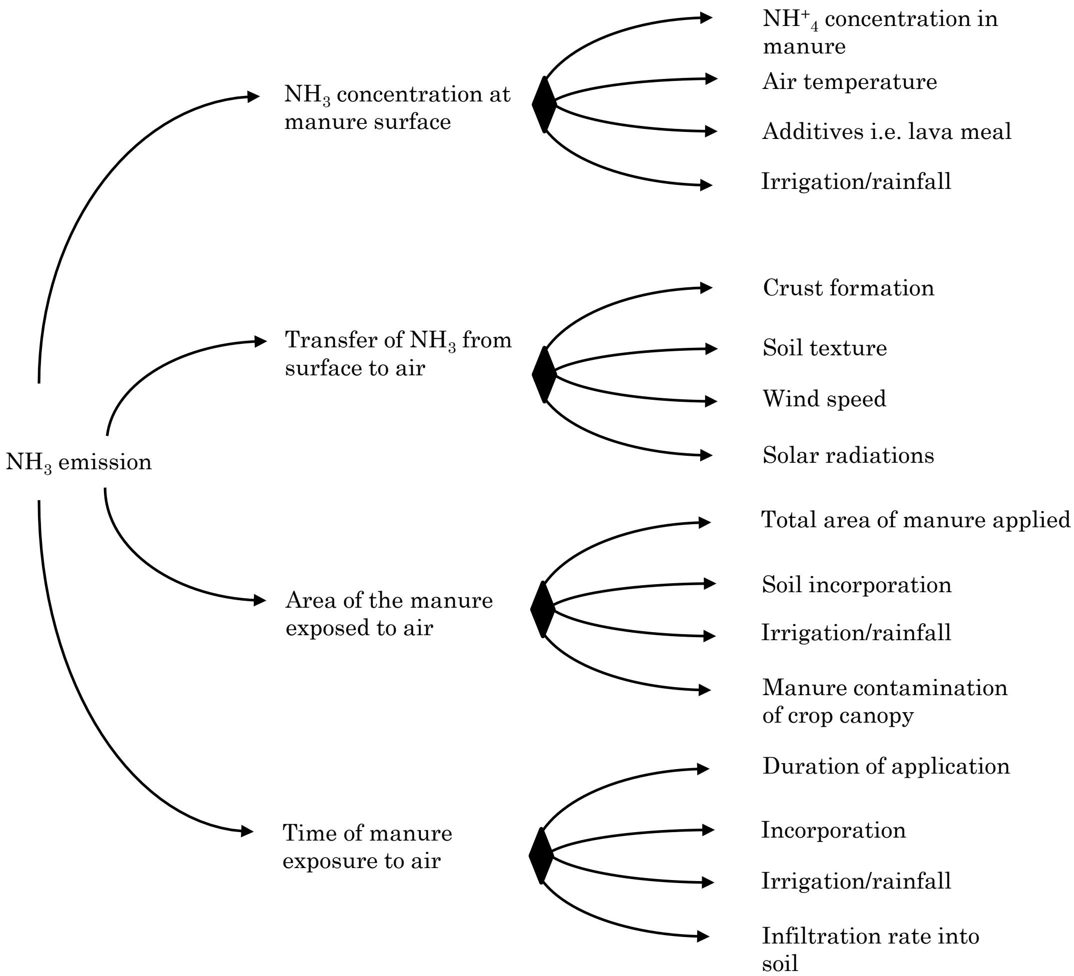

Fig. 1.2. Factors affecting NH_3 emission from field-applied manure (adapted from Sommer and Hutchings 2001).

emission during or after field application of manure. So far, only a few practices have been identified that reduce NH_3 emissions following land application of solid manure (Sommer and Hutchings 2001; Webb et al. 2010). Rapid incorporation of solid manure into the soil after application is a well-known strategy to reduce NH_3 emission (Webb et al. 2004, 2010). However, this cannot be practiced easily in (a) soils containing stones or remnants of tree stubs, (b) vegetated soil i.e. grassland, (c) farms lacking access to powerful machinery, (d) soils containing stones and remnant of tree stubs, and (e) situations where soil cultivation can promote wind erosion (McGinn and Sommer 2007; Webb et al. 2010). Therefore, it is crucial to develop other approaches to reduce NH_3 emissions for these conditions.

1.4.2. Plant N utilization

Solid cattle manure provides a valuable source of plant N nutrition, if managed properly (Schröder 2005). After soil application, part of the NH_4^+-N from the manure is immobilised by microbes, fixed by clay and/or adsorbed on negatively charged surfaces. This immobilised and retained N as well as the initial organic N fraction of applied manure has to be first mineralised or desorbed before it is available for plant uptake. All these N transformations are controlled by soil factors i.e. soil texture (Sørensen and Jensen 1995a), soil characteristics (Schjonning et al. 1999), microbial activity (Bengtsson et al. 2003), and environmental factors (Kätterer et al. 1998; Watts et al. 2007). Despite of this, typical values of plant available N from a given animal manure types during one growing season are provided in handbooks for farmers, irrespective of soil type. In the past, several attempts have been made to examine the effects of soil physical and chemical characteristics on manure N mineralisation, but nearly all of this work has been carried out in the absence of plants (e.g. Chescheir et al. 1986; Sørensen and Jensen 1995a, 1995b; Thomsen and Olesen 2000). This leads to underestimation of net N mineralisation and hence the amount of plant available N (Jonasson et al. 2006). The cropped soil is known to influence the mineralisation processes by (i) release of energy sources through root exudates thus stimulating microbial activities (Bais et al. 2006) and (ii) competition of N between soil biota and plants (Hodge et al. 2000). Therefore, accurate estimation of N mineralisation and plant N recovery from a given animal manure when applied to a certain soil type is essential for effective use of manure N.

Apart from the effect of soil types, N fertiliser value of solid cattle manure is greatly influenced by its storage method which not only affects N losses but also determines the characteristics of the end product. Anaerobic storage transforms high molecular weight compounds (e.g. plant fibre, microbial and metabolic proteins) into easily degradable and low molecular weight compounds such as fatty acids and therefore increases the NH_4^+-N content of manure (Kirchmann and Witter 1989; Van Faassen and Van Dijk 1987). The organic matter decomposed under this method comprises mainly of cellulose, hemicellulose and soluble compounds. Under aerobic conditions, a large part of the manure NH_4^+-N can be lost via NH_3 volatilisation or transformed into organic N. In addition, humified organic material of high stability with a low C/N ratio is produced (Kirchmann 1985). Consequently, decomposition, mineralisation and microbial activity in soil will be less after application of aerobically than anaerobically stored manure (Thomsen and Olesen 2000).

Because of the slow-release characteristics of the organically bound manure N, only a small fraction of the applied N from solid cattle manure becomes plant available during the year of application (Schröder et al. 2007). The remaining N will be mineralised to a certain extent in the following years (Gutser et al. 2005; Muñoz et al. 2008). Although research investigating the residual N fertilising effects of solid cattle manure is scarce, positive residual effects on crop N recovery and dry matter (DM) have been reported (Dilz et al. 1990; Paul and Beauchamp 1993; Eghball and Power 1999; Schröder et al. 2007; Muñoz et al. 2008). However, to our knowledge no attention has been given to estimate and compare the residual N recovery from solid manure stored under different methods including anaerobic storage.

1.5. Need of this study

Solid cattle manure is a valuable source of plant nutrients but may cause agro-environmental problems if its utilisation is inefficient due to poor management. In the industrialised world the intensification of cattle husbandry systems and particularly their manure component turned them into a major source of environmental pollution. Though, in the developing world N losses from animal manure are more associated with its reduction of the N fertiliser value than pollution problems. However, in both situations, it is crucial to reduce N losses from the manure management system.

Of the total N losses from the solid cattle manure management chain, highest losses are likely associated with the storage and application phases. So far, only a few attempts have been made to reduce N losses from these steps since the focus was on slurry management in the last few decades. Of the few attempts so far, nearly all of the work has been focused at the source level (i.e. NH_3 emission from manure storage or application) aimed at investigating the effectiveness of potential mitigation measures and estimating emission factors for that particular source. I believe that it is indispensable to take also into account the downstream impacts of the mitigating strategies e.g. effects of storage methods on N losses, manure disappearance, N release pattern, crop N recovery and crop DM yield after land application on grassland and arable land. This all with the overall aim is to identify and optimise the solid cattle manure management practices for efficient recycling of N within the livestock-manure-soil-crop continuum (Fig. 1.1).

1.6. Objectives of the thesis

This thesis aimed to increase the understanding of the factors controlling N losses from solid cattle manure during storage and following application, and to develop and evaluate alternative strategies to reduce these losses and improve crop N utilisation. The specific objectives of this work were to:

- study the interactions between animal manures and soil types on N mineralisation and plant N recovery
- investigate the effects of storage conditions on (i) magnitude and pathways of C and N losses during storage of solid cattle manure and (ii) crop N recovery as well as DM yield
- examine manure disappearance rates, N release pattern and herbage N recovery during the year of application and the year thereafter from surface applied SCM subjected to different storage conditions, and
- analyse the effect of various application strategies on NH_3 emissions and/or crop N recovery from applied SCM to grassland and arable (maize) land

1.7. Outline of the thesis

This thesis consists of six chapters including this general introduction **(Chapter 1)**. Chapters 2 to 5 present the main results of the study. These chapters have been written as independent research papers that were published in or submitted to international peer-reviewed journals. Therefore, a slight overlap could occur between the general introduction of this thesis and the introduction of some papers.

Chapter 2 was published in 2012 and describes the mineralisation and herbage recovery of N after application of diverging animal manures to various soil types. The relatively lower mineralisation and N recovery from solid cattle manure on each soil type foster our interest to continue research on this source by exploring various options during its management chain (storage and field application) to improve its agro-environmental value.

Chapter 3, submitted to a scientific journal, presents the mass and nutrient balances of solid cattle manure subjected to various storage conditions. Also, it describes the emissions of CH_4, CO_2, NH_3, N_2O, and C as well as N leaching from the manure during storage. Additionally, the effects of contrasting storage methods on manure N utilisation by maize as a test crop are discussed.

Chapter 4, published in 2012, presents (i) total C and N losses during storage, and (ii) first-year and residual DM and N degradability in the field from solid cattle manure subjected to different conditions. Moreover, this chapter also explains the herbage N recovery over two consecutive years after a single application of manure.

Chapter 5, published in 2012, explains the effects of lava meal and irrigation on NH_3 emissions and herbage apparent N recovery from grassland application of solid cattle manure. In addition, the interaction of lava meal and irrigation is treated.

Chapter 6 discusses the main findings and overall contribution of this thesis to new insights. Moreover, some future directions of research are indicated for a better understanding of the processes involved and the optimisation of management strategies to further improve on-farm N cycling from the solid cattle manure management systems.

1.8. References

Annonymous (2001) Directive 2001/81/EC of the European parliament and of the council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants. European parliament and the council of the European union, pp 14

Bais HP, Weir TL, Perry LG, Gilroy S, Vivanco JM (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. Annu Rev Plant Biol 57:233-266

Bengtsson G, Bengtson P, Månsson KF (2003) Gross nitrogen mineralization-, immobilization-, and nitrification rates as a function of soil C/N ratio and microbial activity. Soil Biol Biochem 35:143-154

Chadwick DR (2005) Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: Effect of compaction and covering. Atmos Environ 39:787-799

Chescheir GM, Westerman PW, Safley Jr LM (1986) Laboratory methods for estimating available nitrogen in manures and sludges. Agr Wastes 18:175-195

Dietzell B (1897) Experiments on the conservation of barnyard manure (in German). Landwirtsch Versuchs-stat 48:11-187

Dilz K, Postmus J, Prins WH (1990) Residual effect of long-term applications of farmyard manure to silage maize - A case study to test the Sluijsmans-Kolenbrander model. Fer Res 26:249-252

Eghball B, Power JF (1999) Phosphorus- and nitrogen-based manure and compost applications: Corn production and soil phosphorus. Soil Sci Soc Amer J 63:895-901

Eghball B, Power JF, Gilley JE, Doran JW (1997) Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J Environ Qual 26:189-193

Ellen H, Groenestein K, Smith M (2007) Emissions from storage of solid manure (in Dutch). Animal Sciences Group, Wageningen University, The Netherlands, pp 1-19

Gilhespy SL, Webb J, Chadwick DR, Misselbrook TH, Kay R, Camp V, Retter AL, Bason A (2009) Will additional straw bedding in buildings housing cattle and pigs reduce ammonia emissions? Biosyst Eng 102:180-189

Gutser R, Ebertseder T, Weber A, Schraml M, Schmidhalter U (2005) Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. J Plant Nutr Soil Sci 168:439-446

Haas G, Caspari B, Köpke U (2002) Nutrient cycling in organic farms: stall balance of a suckler cow herd and beef bulls. Nutr Cycl Agroecosyst 64:225-230

Hansen NA (1928) Experiments with manure at the agriculture station of Aaslev 1911-1926. Tidsskrift Planteavl 34:374-523

Hodge A, Stewart J, Robinson D, Griffiths BS, Fitter AH (2000) Competition between Roots and Soil Micro-Organisms for Nutrients from Nitrogen-Rich Patches of Varying Complexity. J Ecol 88:150-164

Huijsmans JFM, Mosquera J, Hol JMG (2007) Ammonia emission during spreading of solid manure (in Dutch). Plant Research International, Wageningen, The Netherlands, pp 20

Hutchings NJ, Sommer SG, Andersen JM, Asman WAH (2001) A detailed ammonia emission inventory for Denmark. Atmos Environ 35:1959-1968

Jonasson S, Castro J, Michelsen A (2006) Interactions between plants, litter and microbes in cycling of nitrogen and phosphorus in the arctic. Soil Biol Biochem 38:526-532

Kätterer T, Reichstein M, Andrén O, Lomander A (1998) Temperature dependence of organic matter decomposition: A critical review using literature data analyzed with different models. Biol Fertil Soils 27:258-262

Kirchmann H (1985) Losses, plant uptake and utilization of manure nitrogen during a production cycle. Acta Agri Scand Suppl 24:1-77

Kirchmann H, Witter E (1989) Ammonia volatilization during aerobic and anaerobic manure decomposition. Plant Soil 115:35-41

Krause H (1890) On nitrogen losses from decomposing organic matter and possibilities for a reduction and protection (in German). J Landwirtsch 38:1-64

Larney FJ, Buckley KE, Hao X, McCaughey WP (2006) Fresh, stockpiled, and composted beef cattle feedlot manure: Nutrient levels and mass balance estimates in Alberta and Manitoba. J Environ Qual 35:1844-1854

McGinn SM, Sommer SG (2007) Ammonia emissions from land-applied beef cattle manure. Can J Soil Sci 87:345-352

Miller DN, Berry ED (2005) Cattle feedlot soil moisture and manure content: I. Impacts on greenhouse gases, odor compounds, nitrogen losses, and dust. J Environ Qual 34:644-655

Mosquera J, Hol JMG, Monteny GJ (2006) Gaseous emissions from a deep litter farming system for dairy cattle. In: Soliva CR, Takahashi J, Kreuzer M (ed), Int Congr Ser, pp. 291-294

Muñoz GR, Kelling KA, Rylant KE, Zhu J (2008) Field evaluation of nitrogen availability from fresh and composted manure. J Environ Qual 37:944-955

Ndegwa PM, Hristov AN, Arogo J, Sheffield RE (2008) A review of ammonia emission mitigation techniques for concentrated animal feeding operations. Biosyst Eng 100:453-469

Oenema O, Bannink A, Sommer SG, Velthof GL (2001) Chapter 10 - Gaseous Nitrogen Emissions from Livestock Farming Systems. In: Hatfield RFFaJL (ed) Nitrogen in the environment: Sources, Problems, and Management. Elsevier Science, Amsterdam, the Netherlands, pp 255-289

Oenema O, Tamminga S (2005) Nitrogen in global animal production and management options for improving nitrogen use efficiency. Sci China Ser C Life Sci 48 (2):871-887

Oenema O, Bleeker A, Braathen NA, Velthof GL (2011) Nitrogen in current European policies. In: Sutton MA, Howard CM, Erisman JW, Billen G, Bleeker A, Grennfelt P, Grinsven H, van Grizzetti B (ed) The European nitrogen assessment. Sources, effects and policy perspectives . Cambridge University Press, UK pp 62-81

Paul JW, Beauchamp EG (1993) Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. Can J Soil Sci 73:253-266

Pearson J, Stewart GR (1993) The deposition of atmospheric ammonia and its effects on plants. New Phytol 125:283-305

Petersen SO, Sommer SG, Béline F, Burton C, Dach J, Dourmad JY, Leip A, Misselbrook T, Nicholson F, Poulsen HD, Provolo G, Sørensen P, Vinnerås B, Weiske A, Bernal MP, Böhm R, Juhász C, Mihelic R (2007) Recycling of livestock manure in a whole-farm perspective. Livestock Sci 112:180-191

Rauhe K, Koepkev V (1967) The influence of different methods of farmyard manure storage on the losses of nitrogen and organic matter. Albrecht Thaer Archiv 11:541-548

Ravishankara AR, Daniel JS, Portmann RW (2009) Nitrous Oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st Century. Science 326:123-125

Rufino MC, Tittonell P, van Wijk MT, Castellanos-Navarrete A, Delve RJ, de Ridder N, Giller KE (2007) Manure as a key resource within smallholder farming systems: analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livestock Sci 112:273–287

Sagoo E, Williams JR, Chambers BJ, Boyles LO, Matthews R, Chadwick DR (2007) Integrated management practices to minimise losses and maximise the crop nitrogen value of broiler litter. Biosyst Eng 97:512-519

Schjonning P, Thomsen IK, Moberg JP, de Jonge J, Kristensen K, Christensen BT (1999) Turnover of organic matter in differently textured soils, I: Physical characteristics of structurally disturbed and intact soils. Geoderma 80:177-198

Schröder JJ, Uenk D, Hilhorst GJ (2007) Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant Soil 299:83-99

Schröder J (2005) Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Bioresour Technol 96 (2):253-261

Sheldrick W, Keith Syers J, Lingard J (2003) Contribution of livestock excreta to nutrient balances. Nutr Cycl Agroecosyst 66:119-131

Siegel O, Meyer L (1938) Investigation on storage of farmyard manure. Bodenl Pfl ernahr 7:190-199

Sommer SG, Hutchings NJ (2001) Ammonia emission from field applied manure and its reduction - Invited paper. Eur J Agron 15:1-15

Sørensen P, Jensen ES (1995a) Mineralization of carbon and nitrogen from fresh and anaerobically stored sheep manure in soils of different texture. Biol Fert Soils 19:29-35

Sørensen P, Jensen ES (1995b) Mineralization-immobilization and plant uptake of nitrogen as influenced by the spatial distribution of cattle slurry in soils of different texture. Plant Soil 173:283-291

Tamminga S (1992) Nutrition Management of Dairy Cows as a Contribution to Pollution Control. J Dairy Sci 75:345-357

Thomsen IK, Olesen JE (2000) C and N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. J Agric Sci Cambr 135:151-159

Van der Meer H, Unwin R, van Dijk TA, Ennik GC (1987) Animal manure on grassland and fodder crops. Fertilizer or waste? Martinus Nijhoff publishers Dordrecht, the Netherlands

Van Faassen HG, van Dijk H (1987) Manure as a source of nitrogen and phosphorus in soils. In: van der Meer H, Unwin R, van Dijk TA, Ennik GC (ed) Animal manure on grassland and fodder crops. Fertilizer or waste? Martinus Nijhoff publishers, Dordrecht, the Netherlands pp 27-45

Virri T (1941) Invetigation about farmyard manure.1. Nitrogen losses in the form of ammonia volatilization. Valt. Maatalouskoetoiminnan 116:1-113

Watts DB, Torbert HA, Prior SA (2007) Mineralization of Nitrogen in Soils Amended with Dairy Manure as Affected by Wetting/Drying Cycles. Comm Soil Sci Plant Anal 38:2103-2116

Webb J, Chadwick D, Ellis S (2004) Emissions of ammonia and nitrous oxide following incorporation into the soil of farmyard manures stored at different densities. Nutr Cycl Agroecosyst 70:67-76

Webb J, Pain B, Bittman S, Morgan J (2010) The impacts of manure application methods on emissions of ammonia, nitrous oxide and on crop response—A review. Agr Ecosyst Environ 137:39-46

Chapter 2

Mineralisation and herbage recovery of animal manure nitrogen after application to various soil types

G.M. Shah, M.I. Rashid, G.A. Shah, J.C.J. Groot, E.A. Lantinga

Abstract

Typical values of plant available nitrogen (N) from animal manures are provided in fertiliser recommendation schemes. However, only a few attempts have been made thus far to study the variation in these values among contrasting soil types. The objective of this study was to examine the interactions between animal manure and soil types on N mineralisation and total plant N recovery (shoots + roots) during one growing season. A pot experiment was conducted in a greenhouse during a growth period of 180 days. Experimental treatments included solid cattle manure (SCM), cattle slurry (CS) and poultry manure (PM), all applied to sandy, clay and peat soils sown with perennial ryegrass. Total N application rate was 120 kg ha^{-1}. There were clear interactions ($P < 0.05$) between the manure and soil types on N mineralisation and total plant N recovery. For each manure type, both parameters followed the pattern ($P < 0.01$): peat > sandy > clay. In case of the peat soil, net mineralisation of the applied organic N was on average 90% from PM, 39% from SCM and 26% from CS. However, in the clay soil a positive net N mineralisation occurred only from PM (42%). Besides, significant proportions of the applied mineral N from SCM (17%) and CS (35%) were immobilised in this soil type. Consequently, apparent total plant N recovery was highest in the peat soil with values of 80, 57 and 50% from PM, CS and SCM, respectively. In contrast, these values were only 57, 28 and 15% for the clay soil. It is concluded that wide variations do exist in the extent of net N mineralisation and plant N recovery from a given animal manure type when applied to diverging soil types. This indicates the need for more soil-specific manure fertiliser recommendations.

Keywords: Solid cattle manure, Cattle slurry, Poultry manur, Soil type, Mineralisation, Nitrogen utilisation, Fertiliser recommendations

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2.1. Introduction

Typical values of plant available nitrogen (N) from animal manures during one growing season are provided in handbooks for farmers. According to MAFF (1979) and Brockman (1988) these are 25% of the N_{total} from solid cattle manure, 50% from cattle slurry and 60% from poultry manure in the year of their application. However, in reality these values may vary widely after addition of the same manure source to contrasting soil types (Castellanos and Pratt 1981; Chae and Tabatabai 1986; Sørensen and Jensen 1995a and 1995b).

After soil application, part of the ammonium-N (NH_4^+-N) from manure is immobilised by microbes, fixed by clay and/or adsorbed on negatively charged surfaces. This immobilised and retained N as well as the organic N fraction of applied manure has to be first mineralised or desorbed before it is available for plant uptake. All these N transformations are rather complex and controlled by a number of soil factors i.e. soil texture (Sørensen and Jensen 1995a), soil characteristics (Schjonning et al. 1999), microbial activity (Bengtsson et al. 2003) and environmental factors (Katterer et al. 1998; Watts et al. 2007). It has been shown in earlier studies that the net N mineralisation rate of manure is negatively correlated with the soil clay content (Castellanos and Pratt 1981; Chescheir et al. 1986; Sørensen and Jensen 1995a and 1995b). The three main reasons for this phenomenon are (i) fixation of NH_4^+-N into the interlayer spaces of clay minerals (Nieder et al. 2011), (ii) entrapment of organic N compounds in soil aggregates inaccessible to microbes and (iii) physical protection of the microbial biomass in the soil structure (Van Veen and Kuikman 1990). According to Magdoff (1978), N mineralisation from added organic materials can also be affected by the rate of mineralisation of native soil organic matter (OM). It is well-known that agronomic practices that build-up soil OM greatly improve soil fertility and thereby the potential for N mineralisation (Wood and Edwards 1992; Liu et al. 2006). It is therefore expected that soil types varying in all of these characteristics will have diverging consequences for the net availability of animal manure N to crops.

Several attempts have been made to examine the effects of soil physical and chemical characteristics on manure N mineralisation, but nearly all of this work has been carried out in the absence of plants (Castellanos and Pratt 1981; Chescheir et al. 1986; Sørensen and Jensen 1995a and 1995b; Thomsen and Olesen 2000). Jonasson et al. (2006) demonstrated that measurements of net N mineralisation in a cropless soil yield underestimations of plant N availability. Growing plants are known to enhance the rate of N turnover in the rhizosphere (Jonasson et al. 2006) since root excretions of energy sources stimulate the soil microbial biomass and its activity (Bais et al. 2006). In addition, competition between roots and micro-organisms for N may also affect net N mineralisation (Hodge et al. 2000). Therefore, estimation of the influences that cropped soils could have on N mineralisation and overall plant N recovery from amended manure is essential for more effective use of fertiliser resources. The aim of the current work thus was to study the interactions between three animal manure (solid cattle manure, cattle slurry and poultry manure) and soil types (sandy, clay and peat) on N mineralisation and plant N recovery during one growing season with perennial ryegrass (*Lolium perenne* L.) as test crop.

2.2. Materials and methods

To pursue the objective outlined above, a pot experiment was carried out for 180 days under controlled environmental conditions in a greenhouse of Wageningen University and Research Centre, the Netherlands (latitude 55°99'N and longitude 5°66'E). In order to focus only on the main research question we have carried out this experiment under glasshouse conditions and not outdoors to avoid disturbing effects of changing weather conditions.

2.2.1. Soils and manures: collection and characteristics

Sandy, clay and peat soils from different regions of the Netherlands were used in this explorative study. All these soils were collected from a depth of 0-30 cm. After collection from the field, representative samples were taken to determine soil texture and contents of organic matter (OM), total carbon (C), total N, NH_4^+-N, nitrate-N (NO_3^--N), total phosphorus (P), total potassium (K), magnesium (Mg), sodium (Na), cation exchange capacity (CEC) and pH (Table 2.1). Soil texture was measured using laser diffractometry (Coulter LS 230, Beckman Coulter, USA) as described by Buurman et al. (2001). The soil OM content was determined after drying the samples at 105°C for 24 hours and subsequent ignition of the dried samples at 525°C for 6 hours. Total N was measured after Kjeldahl digestion (MAFF 1986). The NH_4^+-N and NO_3^--N contents were measured using a 1:10 soil/0.01M $CaCl_2$ extract by means of segment-flow analysis (Houba et al. 1989) and this extract was also used for determining the

Table 2.1. Physical and chemical properties of the soils.

Soil	OM	Texture[a] (%)			N_{total}	NH_4-N	NO_3-N	P_{total}	K_{total}	Mg	Na	CEC	C/N	pH
	(%)	20-2000 (µm)	2-20 (µm)	< 2 (µm)	(mg kg^{-1})							(cmol kg^{-1})		
Sandy	2.4	86	10	4	1016	2.5	13.0	3.6	17	120	7	3.3	14	5.7
Clay	2.8	9	57	34	1440	1.6	13.3	1.1	37	102	12	19.3	10	7.4
Peat	31.6	32	48	20	11896	7.5	72.9	1.3	335	381	78	41.8	13	4.7

[a] = < 2 µm (clay), 2-20 µm (silt) and 20-2000 µm (sand).

soil pH using a pH meter (inoLab pH meter level 1, WTW GmbH & Co. KG, Germany). Total CEC, C, P, K, Mg and Na were determined according to the procedures described by Houba et al. (1989).

Three animal manures were applied to each soil type: solid cattle manure (SCM), cattle slurry (CS) and poultry manure (PM). The SCM was collected from a tying stall barn where cereal straw (wheat and barley mixture) was used as bedding material at a daily rate of 5 kg per livestock unit (i.e. 500 kg live weight). The CS was taken from a cubicle barn where urine and faeces were collected underneath a slatted floor while the PM produced by broilers consisted of bedding material (chopped straw) and a mixture of excreta. All the manures were applied directly from barns to the soils without intermediate storage. Before application, manures were sampled and analysed for contents of total C, total N, mineral N (NH_4^+-N + NO_3^--N), dry matter (DM) and OM (Table 2.2). Total C was determined following digestion with dichromate (MAFF 1986). Total N was measured after Kjeldahl digestion (MAFF 1986). Mineral N was measured in a 1:10 manure/0.01M $CaCl_2$ extract by means of segment-flow analysis (Houba et al. 1989). The DM content was determined after drying the samples at 105°C for 24 hours. Subsequently, OM content was determined gravimetrically through ignition of the dried samples at 525°C for 6 hours (Anonymous 1998).

2.2.2. Experimental setup and treatments

All the soils were sieved using a 4 mm mesh frame in order to remove plant roots and other debris. Thereafter, plastic pots were filled with the three soils; amounts were ranging from 9-15 kg per pot depending on their bulk densities. Each pot (height 30 cm, surface area 0.071 m^2) with four holes in the bottom was kept on a plastic plate in order to collect and recycle leachate if any.

Table 2.2. Chemical characteristics of the manures.

Manure	DM (%)	OM (%)	N_{total} (g kg^{-1} of DM)	$^{a}N_{mineral}$ (g kg^{-1} of DM)	$N_{organic}$ (g kg^{-1} of DM)	C/N
Solid cattle manure	19.7	14.1	32.5	6.3	26.2	10
Cattle slurry	10.0	7.2	38.9	17.0	22.0	8
Poultry manure (broiler)	41.6	25.8	37.7	10.1	27.6	7

^{a} = Sum of NH_4^+-N and NO_3^--N.

Subsequently, the manures were applied to the soils at an application rate of 120 kg N ha^{-1} and manually incorporated in the top 10 cm in order to avoid ammonia emission (Webb et al. 2010). In addition, a control of each soil type was included with similar soil preparation, but without manure addition. The treatments were arranged in a randomised complete block design with three replicates.

Two days after manure application, perennial ryegrass was sown in all of the pots at a seed rate of 0.3 g pot^{-1}. The environmental conditions were controlled to provide 16 h of daylight and 8 h darkness with temperatures of 18°C and 12°C, respectively. The soil moisture content was maintained at ca. 60% water holding capacity (WHC) throughout the experimental period in order to avoid denitrification losses (Mosier et al. 2002). For this purpose, water was applied daily using a hand sprinkler with extreme care whilst following the increase in WHC with a low-cost moisture meter (FY-901, Hangzhou FCJ I&E Co., Ltd, China).

2.2.3. Soil sampling and analysis

At the end of the experiment, soil samples were collected to estimate the contents of residual mineral N (NH_4^+-N + NO_3^--N) and pH in all treatments. To this end, three random samples were taken from each pot with a soil auger (~1.5 cm diameter) from top to bottom. After sampling, soils were dried in an oven at 40°C for 48 hours and ground to pass a 1 mm sieve. Thereafter, all the samples were analysed for mineral N using a 1:10 soil/0.01 M $CaCl_2$ extract by means of segment-flow analysis (Houba et al. 1989). Soil pH was measured from the same extract using a pH meter.

2.2.4. Plant harvesting

2.2.4.1. *Shoot harvesting*

During the entire experimental period of 6 months, the grass plants were harvested three times: 60, 120 and 180 days after sowing. During the 1st and 2nd harvest, plants were clipped with a scissor 4 cm above soil level, whereas during the 3rd harvest they were cut at ground level. Each time, fresh shoot biomass from the pots was measured and representative samples were oven-dried at 70°C for 48 hours (Sharkey 1970), weighed, ground to pass a 1 mm sieve and analysed for total N content after Kjeldahl digestion as described by Houba et al. (1989). Finally, shoot N uptake from each pot was calculated by multiplying the shoot

DM yield with its N content.

2.2.4.2. *Root harvesting*

At the final harvest, roots of the grass were separated from soil in each pot in order to estimate total DM yield and N uptake. For this purpose, the whole soil clump from a pot was taken out and placed in a container filled with cold water. After 2 hours of soaking, the clump was manually divided into 6-8 pieces. These were taken out of the container one by one and placed on a 0.5 mm mesh frame to separate roots from soil with a jet of tap water. In addition, the remaining roots were recovered by decanting the soil-water mixture through a sieve with the same mesh size. After separation from the soil, the root material was dried in an oven at 70°C for 48 hours (Sharkey 1970), weighed, ground to pass a 1 mm sieve and analysed for total N content through Kjeldahl digestion (Houba et al. 1989). Subsequently, root N yield of each pot was calculated by multiplying the root DM yield with its N content. Together with the final amount of soil mineral N, this enabled us to construct an N balance in order to calculate the fraction of net mineralised organic manure N as described by Yang et al. (2004).

2.2.5. Plant N recovery calculations

At the end of the experiment, shoot N uptake from each harvest as well as root N uptake at final harvest were summed to calculate total N uptake by the grass from each treatment. Subsequently, total N recovery (TNR) was calculated as:

$$\mathrm{TNR}\ (\%) = 100 * \frac{(\mathrm{TNU}_{\mathrm{manured}}) - (\mathrm{TNU}_{\mathrm{control}})}{\mathrm{TN}_{\mathrm{applied}}} \qquad (2.1)$$

Where $TNU_{manured}$ is total N uptake (g m^{-2}) by the grass from manured pots, $TNU_{control}$ is total N uptake (g m^{-2}) by the grass from unfertilised pots and $TN_{applied}$ is total N applied (g m^{-2}) with manure.

2.2.6. Statistical analysis

Statistical analysis was carried out by analysis of variance using Genstat (13th Edition, VSN International, Hemel Hempstead, UK). Effects of manure type, soil type and their interactions on N mineralisation, and the different DM yield and N uptake parameters were tested. For each variable, if the overall effect was significant, differences among the treatments were further compared using Tukey's test at 5% probability level.

2.3. Results

Average crop N uptakes from all treatments are presented in Table 2.3. Total uptake of N (shoots + roots) by the grass from unfertilised soils was highest ($P < 0.05$) from peat soil (Table 2.3), whereas there was no difference ($P > 0.05$) between the sandy and clay soil (Table 2.3). Over the 180 days growth period, total N uptake followed the pattern ($P < 0.001$): PM > CS > SCM in each soil type.

From each manure, TNR by the grass grown in the peat soil was higher ($P < 0.001$) compared to the sandy or clay soil. There were clear interactions ($P < 0.05$) between the different manure and soil types (Fig. 2.1). On average, 80% of the total N applied was recovered from PM, 57% from CS and 50% from SCM in the peat soil (Fig. 2.1). In contrast, the respective values were only 57, 28 and 15% for the clay soil. The TNR from both SCM and CS was lower in the clay than in the sandy soil ($P < 0.05$), but for PM there was no difference between these soil types (Fig. 2.1). Of the TNR from all treatments, the highest contribution came from the 1st grass harvest, and the amount of recovered N gradually decreased in the two subsequent harvests (data not shown).

The distribution between shoots and roots of N taken up by the grass differed greatly among the soil and manure types. On average, a relatively high proportion of the total N uptake ended up in the roots of grass grown in the sandy and clay soils (~ 21%) compared to only about 7% in the peat treatments (Table 2.3). Visual observations revealed that the roots in peat soil were concentrated in the top 10 cm of soil, whereas these were distributed throughout the whole soil profile in case of the sandy and clay pots. In the latter two soil types, the tendency for investment of N in the roots differed among the manure types in the order: SCM > CS > PM (Table 2.3). However, in the peat soil no differences were observed (Table 2.3).

Calculation of the net N balance over 180 days revealed the interactions ($P < 0.05$) between the manure and soil types on net N recovery of organic N (Table 2.4). This net N recovery was due to the net mineralisation in the treatments. Overall, N mineralisation from all manures was highest in the peat soil ($P < 0.001$). Net mineralisation of organic N from SCM and CS occurred only in the sandy soil (7.6 and 2.9% of the initial $N_{organic}$, respectively) and the peat soil (38.5 and 26.6%, respectively) (Table 2.4). In contrast, part of the mineral N from SCM (~4% of the initial $N_{organic}$) and CS (~27%) was net immobilised in the clay soil. On the other hand, PM showed net mineralisation (42-90% of initial organic N) in

Table 2.3. DM yield and N uptake by perennial ryegrass after 180 days of growth period.

	DM yield (g m^{-2})			DM_{root} (% of total DM)	N uptake (g m^{-2})			N_{root} (% of total uptake)	NUE[a]	pH $CaCl_2$
	Roots	Shoots	Total		Roots	Shoots	Total			
Sandy										
Control	187 de	394 gh	581 ef	32	1.4 cd	5.2 fgh	6.6 gh	21	88	6.02
SCM	277 ab	532 def	809 bc	34	2.5 a	6.9 f	9.4 f	27	86	6.08
PM	295 ab	726 ab	1021 a	29	1.9 bc	12.0 d	13.9 d	14	74	6.09
CS	322 a	672 abc	994 a	32	2.3 ab	9.5 e	11.8 e	20	84	6.01
Clay										
Control	145 ef	330 h	475 f	31	1.1 e	3.8 h	4.8 h	22	99	7.62
SCM	211 cd	420 fgh	631 e	33	1.7 cd	4.9 gh	6.6 gh	25	96	7.62
PM	220 cd	645 bcd	865 bc	25	1.5 cd	10.1 e	11.6 e	13	75	7.54
CS	263 bc	507 efg	770 cd	34	1.9 abc	6.3 fg	8.2 fg	23	94	7.55
Peat										
Control	88 f	569 cde	657 de	13	1.1 d	16.2 c	17.3 c	6	38	4.77
SCM	98 fg	740 ab	838 bc	12	1.4 cd	21.9 b	23.3 b	6	36	4.70
PM	112 fg	787 a	899 ab	12	1.7 cd	25.2 a	26.9 a	6	33	4.92
CS	123 fg	781 a	904 ab	14	1.8 bc	22.3 b	24.1 b	8	38	4.86
Statistical analysis (P-values)										
MT!!	<0.001	<0.001	<0.001	nd	<0.001	<0.001	<0.001	nd	<0.001	0.711
ST¡	<0.001	<0.001	<0.001	nd	<0.001	<0.001	<0.001	nd	<0.001	<0.001
MT×ST	0.001	0.018	0.003	nd	0.033	<0.001	<0.001	nd	0.189	0.205

[a] = Nitrogen use efficiency (kg DM production per kg N uptake).

!! = Manure type, ¡ = Soil type, nd = Not determined.

*Values followed by different letters within a column are significantly different ($P < 0.05$) from each other.

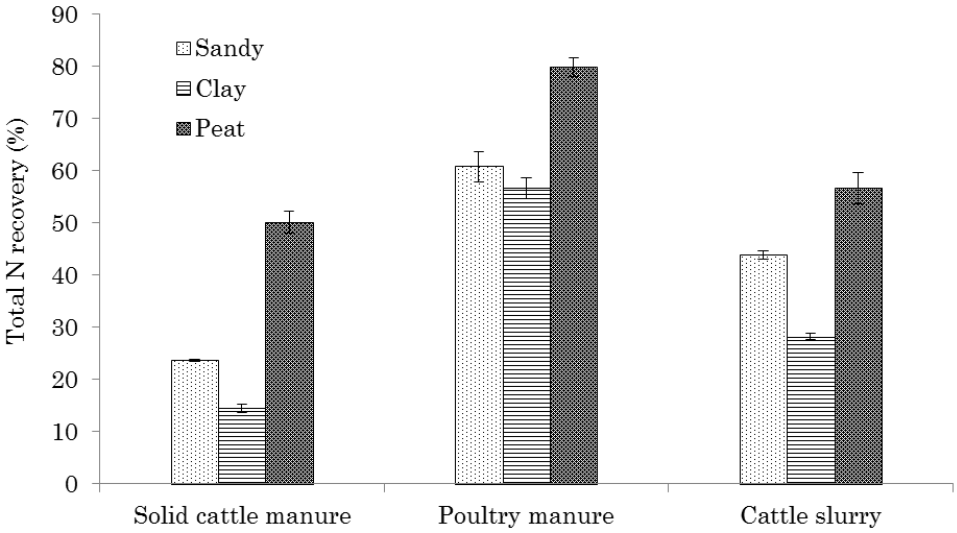


Fig. 2.1. Net recovery of total manure N by perennial ryegrass (shoots + roots) over a period of 180 days. Error bars represent standard error (±) of the mean. Bars with different letters are different from each other at 5% probability level.

all of the soils (Table 2.4).

Total DM production per kg N uptake was significantly influenced by the soil types (Fig. 2.2a and Table 2.3). At the same level of N uptake, the total DM yield of shoots and roots together was much lower for the peat soil than for the sandy or clay soils (Figs. 2.2b and 2.2c). N uptake in grass shoots on peat soil was much higher than for the other soil types (Table 2.3), but the shoot DM yield was not increased proportionally (Fig. 2.2b). As a result, the N content of the grass was ~2.5 times higher in the peat treatments compared to the others, indicating luxury N consumption. The number of grass tillers in the peat soil at final harvest was only about half of that in the other soils (data not shown). Although no data were collected, the leaves of the grass plants produced on peat soil were much wider and longer relative to those produced on the other two soils throughout the experiment.

2.4. Discussion

The effects of soil type on total N uptake, TNR and net N mineralisation from the applied manures were very clear. For each manure type, the values obtained for all these parameters were highest in the peat soil (Tables 2.3 & 2.4 and Fig. 2.1). In addition, plant N uptake from the unfertilised peat soil was also highest (Table 2.3). These observations concur with those of Magdoff (1978) who

Table 2.4. N balance in the pots based on the N addition with manure, total N uptake (shoots + roots) by perennial ryegrass and residual mineral N in the soils over a period of 180 days.

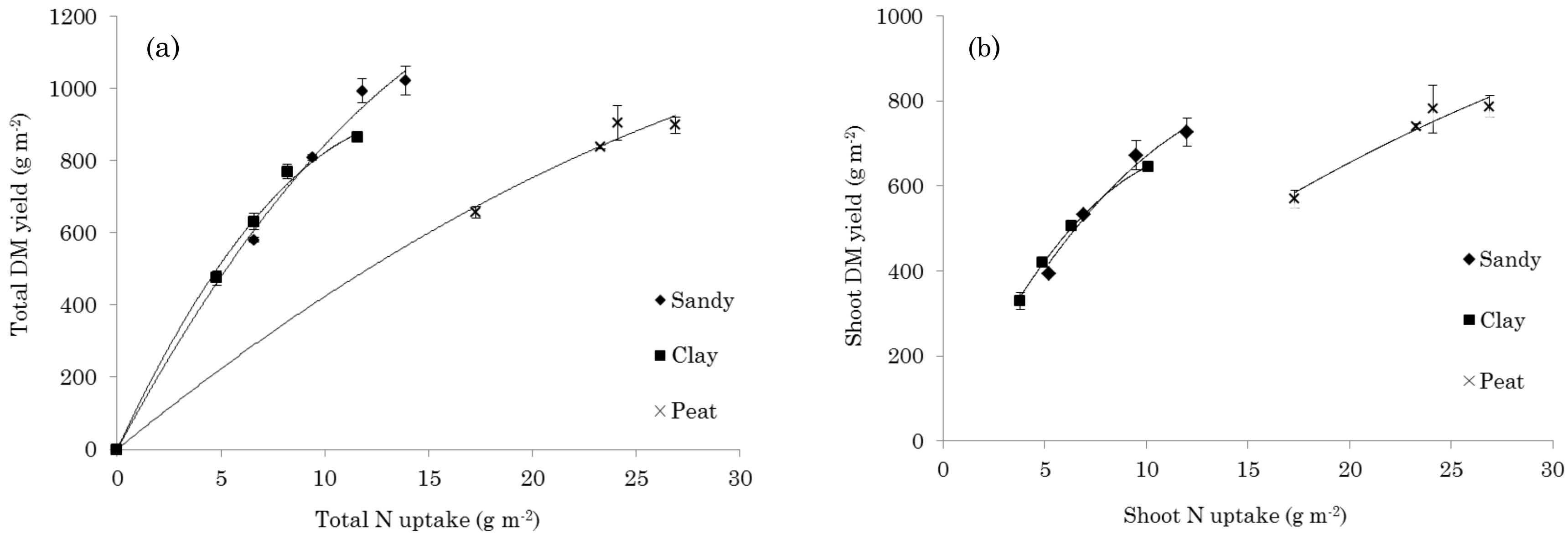
	N applied			N uptake by grass		Final mineral N in soil		Net recovery of organic manure N	
	Total	Mineral	Organic	Total	From manure (g m^{-2})	Total	From manure	A[a]	B[b] (%)
Sandy									
Control	0			6.6		0.86			
SCM	12	2.3	9.7	9.4	2.8	1.10	0.24	0.74 cd	7.6d
PM	12	3.2	8.8	13.9	7.3	1.12	0.26	4.36 b	49.5b
CS	12	5.2	6.8	11.8	5.2	1.06	0.20	0.20 d	2.9d
Clay									
Control	0			4.8		0.73			
SCM	12	2.3	9.7	6.6	1.8	0.83	0.10	-0.40 d	-4.2d
PM	12	3.2	8.8	11.6	6.8	0.79	0.06	3.66 b	41.6b
CS	12	5.2	6.8	8.2	3.4	0.73	0.00	-1.80 e	-26.5e
Peat									
Control	0			17.3		5.05			
SCM	12	2.3	9.7	23.3	6.0	5.08	0.03	3.73 b	38.5bc
PM	12	3.2	8.8	26.9	9.6	6.58	1.53	7.93 a	90.1a
CS	12	5.2	6.8	24.1	6.8	5.26	0.21	1.81 c	26.6c
Statistical analysis (P-values)									
MT!!	N/A	N/A	N/A	<0.001	<0.001	0.016	0.012	<0.001	<0.001
ST¡	N/A	N/A	N/A	<0.001	<0.001	<0.001	0.012	<0.001	<0.001
MT×ST	N/A	N/A	N/A	0.003	0.008	0.023	0.005	0.017	0.021

[a] = [(N uptake from manure + final mineral N from manure in the soil) – mineral N applied with manure].

[b] = [(A/ applied organic manure N)*100].

!! = Manure type, ¡ = Soil type, N/A= Not applicable.

* Values followed by different letters within a column are significantly different (P < 0.05) from each other.



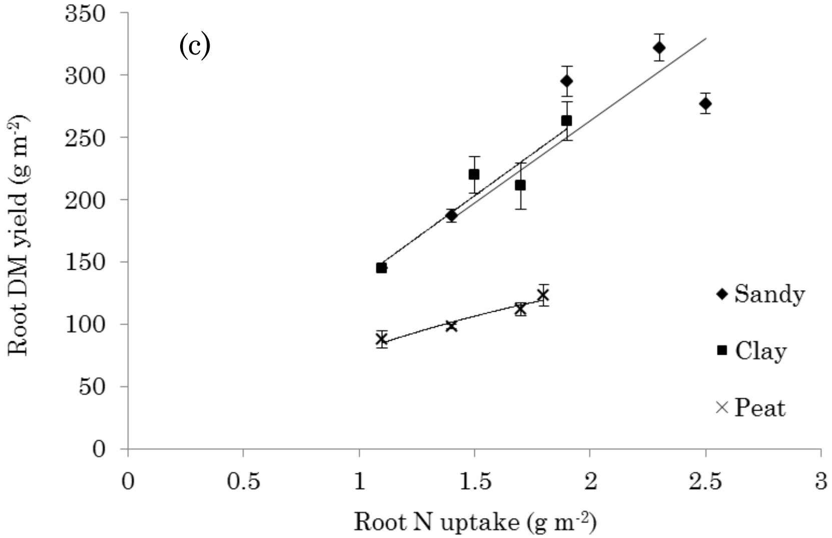


Fig. 2.2. Relationships between (a) total N uptake and total DM yield, (b) shoot N uptake and shoot DM yield, and (c) root N uptake and root DM yield of ryegrass. Symbols represent the observed average values of herbage DM yield from control and manured pots, whereas the continuous lines are the trend lines. Error bars depict standard error (±) of the mean.

concluded that soils with high soil N mineralisation rates do mineralise N from added manure more rapidly compared to soils with lower inherit N availability rates. It should be noted that in our experiment the TNR values and net N mineralisation potential of the peat soil could have been stimulated by the long-term (> 50 years) high input rates of crop residues, ditch sludge and animal manures on the dairy farm where this soil was collected (Sonneveld and Lantinga 2010). This farming practice has led to a build-up of young soil OM including young organic N and thereby increased the potential for N mineralisation (Wood and Edwards 1992; Liu et al. 2006).

Regarding the sandy and clay soils, which both had similar N delivering capacities (Table 2.3), net N immobilisation and lower TNR were observed from SCM and CS in the latter soil type (Table 2.4 and Fig. 2.1). This could be attributed in all probability to its higher clay content (Table 2.1) and not to its higher CEC value, since through the extraction with $CaCl_2$ all NH_4^+ from the cation exchange sites were removed (Stevenson 1982). For this reason, CEC could not have affected the calculated N balance (Table 2.4). At high clay contents, fixation of NH_4^+-N in the interlayers of clay minerals will be enhanced (Nommik and Vahtras 1982; Nieder et al. 2011) and microbial immobilisation of NH_4^+-N will be stimulated (Sørensen and Jensen 1995b). This is corroborated by Chantigny et al. (2004) who also reported greater fixation of NH_4^+ in clay compared to sandy soil.

Net immobilisation of manure N can be higher in soils with higher soil clay content due to greater protection of the microbial biomass with increasing soil clay content (Amato and Ladd 1992). Therefore, a high amount of N retained in the microbial biomass is protected from the predators (i.e. nematodes and micro-arthropods), which in turn results in a lower net N mineralisation rate (Bloem et al. 1997; Laakso et al. 2000). However, this can be affected by the manure characteristics such as water content, which determines the distribution of applied N in the soil profile and thereby could have an influence on the interactions between manure and soil particles (Sørensen and Jensen 1998). It has previously been shown that the interaction between soil type and cattle slurry N mineralisation is influenced by the distribution pattern of the applied slurry in the soil profile (Sørensen and Jensen 1995a). We suggest that after incorporation of CS and SCM with much higher inherited water contents (Table 2.2), their soluble compounds were moved deeper into the soil profile through water flow and diffusion, whereas the solid and larger particles remained at the place of application. During this downward transport process NH_4^+-N from the manures could easily be adsorbed on negatively charged surfaces, metabolised C could be taken up by the micro-organisms and some manure particles could become trapped in the soil matrix and therefore be protected against predation (Petersen et al. 2003). The larger particles of the manures are to be expected to have a high C/N ratio because of the presence of straw and thereby may cause immobilisation in soil (Whitehead et al. 1989). On the other hand, after application of dry PM (Table 2.2) water was initially transported from soil into manure particles before decomposition. Therefore, the micro-organisms utilising N were remained in the manure clumps and as being unprotected from predators this resulted in increased N mineralisation rates (Sørensen and Jensen 1995a). Our results corroborates with Jingguo and Bakken (1989) as well as Sørensen and Jensen (1995a) who reported that in a heterogeneous soil-plant system with N mineralising and immobilising zones, overall net mineralisation and plant uptake of N can be much higher compared to a similar homogenised system.

On each soil type both net N mineralisation and TNR were highest in the PM treatments. This can be related to the diverging chemical characteristics of the three manure types. The contents of mineral N compounds ranged from low (19% of the N_{total}) in SCM to a much higher fraction in CS (44%), while PM had an intermediate value (27%). However, the N fertiliser value of manure is the sum of its mineral N content and the mineraliseable organic N forms. Therefore, the observed higher net N mineralisation and TNR from PM could be attributed to the presence of more readily mineraliseable organic N compounds (Preusch et al. 2002). According to Tyson and Cabrera (2008), PM contains for the greater part easily degradable N compounds, i.e. uric acid, which can represent in the order of 70% of the total N and therefore readily mineralise after soil application. On the other hand, both in CS and SCM the organic N is more strongly bound and therefore less likely to be released quickly (Chadwick et al. 2000). This was clearly reflected in the constructed N balance which showed highest net gain of mineral N through mineralisation from PM (Table 2.4). Compared to our study, somewhat higher values of mineralised N from PM and similar values from SCM and CS were found by Chadwick et al. (2000) in a pot experiment with sandy soil for 199 days.

Of the total N recovered by the grass plants, its distribution between roots and shoots differed greatly among the manure and soil types. In general, a relatively higher proportion of the absorbed N as well as the produced DM was allocated to the belowground organs in the treatments with lower amounts of plant available soil N (Table 2.3). This can be explained using the functional equilibrium concept. According to this approach DM and N distribution between root and shoot is regulated by an equilibrium between root and shoot activity (Marcelis et al. 1998). In N-limited conditions root activity decreases and plants tend to invest more in root growth in order to explore a large volume of soil for N to compensate for this. Consequently, root DM and N yields will increase (Wilson 1988) like in our clay and sandy treatments next to the control. Among the manure types, both these parameters were lowest in case of PM as a result of its high N mineralisation rate (Table 2.4). These findings are also consistent with observations of Gislum and Griffith (2004) who reported relatively lower root N yields at increasing contents of plant available soil N.

Interestingly, the total (shoots + roots) DM yield per kg N uptake was much lower in the peat soil compared to the other two soils as reflected in the calculated NUE (nitrogen use efficiency) values (Table 2.3 and Figs. 2.2b and 2.2c). According to Simon and Lemaire (1987) DM allocation to shoots increases at high N availability resulting in higher rates of leaf expansion and elongation. Consequently, the leaf area index (LAI) will increase faster leading to an earlier onset of self-shading of leaves lower in the canopy. This will lead to an early cessation of appearance of new tillers (Mitchell and Coles 1955; Thomas and Norris 1981). Simon and Lemaire (1987) found that tillering of perennial ryegrass growing outdoors terminates after the LAI has reached a value of about 3, which corresponded with an almost complete elimination of light at the level of the tiller buds near the soil surface. In a greenhouse, where the radiation level is only in the order of 60% of that outdoors (Dayan et al. 1986), this threshold LAI will even be lower. This is an artefact of doing experiments indoors and is a plausible explanation for the observed more or less twofold lower tiller density in our peat treatments. This reduced tiller density is a clear indication that the developmental shift from a source to a sink limitation of photosynthesis has started already early during the growth cycles of the grass plants on peat. As a result, the total DM yield from the peat treatments at an even double level of N uptake still lagged behind those obtained in the sandy pots (Table 2.3). Sink limitation in plant growth imposes next to leaf photosynthesis downregulation (Lantinga et al. 1996; Nebauer 2011) also stimulation of both "wastage" respiration (Amthor 2000) and root exudation of C compounds (Walker et al. 2003).

2.5. Conclusions

This study clearly demonstrated the existence of significant interactions between three animal manure and soil types regarding net manure N mineralisation and total plant N recovery. Overall, both N mineralisation and total plant N recovery were highest from poultry manure compared to cattle slurry and solid cattle manure. For each manure type, their values were highest in the peat soil which was characterised by the greatest N delivering capacity. Between the other two soils with more or less similar N delivering capacities, net N mineralisation and total plant N recovery from both solid cattle manure and cattle slurry were lower in the clay soil. This could be associated with its inherited higher clay content leading to increased microbial immobilisation and fixation of NH_4^+-N. The results from this experiment indicate the need for more soil-specific manure fertiliser recommendations and might be used as a first step to re-define and evaluate manure N mineralisation guidelines and models for the above soil types.

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2.7. References

Amato M, Ladd JN (1992) Decomposition of ^{14}C-labelled glucose and legume material in soils: properties influencing the accumulation of organic residue C and microbial biomass C. Soil Biol Biochem 24:455-464

Amthor JS (2000) The McCree-de Wit-Penning de Vries-Thornley respiration paragigms: 30 years later. Ann Bot 86:1-20

Anonymous (1998) NEN 7432 Manure and derivatives. Determination of the contents of dry matter and organic matter (in Dutch). Gravimetric method. Dutch Standardization Institute (NNI), Delft, the Netherlands

Bais HP, Weir TL, Perry LG, Gilroy S, Vivanco JM (2006) The role of root exudates in rhizosphere interactions with plants and other organisms. Annu Rev Plant Biol 57:233-266

Bengtsson G, Bengtson P, Mansson KF (2003) Gross nitrogen mineralisation-, immobilization-, and nitrification rates as a function of soil C/N ratio and microbial activity. Soil Biol Biochem 35:143-154

Bloem JD, Ruiter P, Bouwman L (1997) Soil food webs and nutrient cycling in agroecosystems. In: Elsas van DJ, Trevors TJ, Wellington HME (ed) Modern soil microbiology. Marcel Dekker, Inc. New York pp 245-275

Brockman JS (1988) Crop nutrition. In: Halley RJ, Soffe RJ (ed) The agriculture note book, 18th edn. London, pp 70-89

Buurman P, Pape T, Reijnveld JA, de Jong F, van Gelder E (2001) Laser-diffraction and pipette-method grain sizing of Dutch sediments: correlations for fine fractions of marine, fluvial, and loess samples. Ned J Geo Sci 80:49–57

Castellanos JZ, Pratt PF (1981) Mineralisation of manure nitrogen-correlation with laboratory indexes. Soil Sci Soc Am J 45:354-357

Chadwick DR, John F, Pain BF, Chambers BJ, Williams J (2000) Plant uptake of nitrogen from the organic nitrogen fraction of animal manures: a laboratory experiment. J Agric Sci 134:159-168

Chae YM, Tabatabai MA (1986) Mineralisation of nitrogen in soils amended with organic wastes. J Environ Qual 15:193-198

Chantigny MH, Angers DA, Morvan T, Pomar C (2004) Dynamics of pig slurry nitrogen in soil and plant as determined with N-15. Soil Sci Soc Am J 68:637–643

Chescheir GM, Westermann PW, Safley LM (1986) Laboratory methods for estimating available nitrogen in manures and sludges. Agric Wastes 18:175-195

Dayan E, Enoch HZ, Fuchs M, Zipori I (1986) Suitability of greenhouse building types and roof cover materials for growth of export tomatoes in the besor region of Israel. I. Effect on climatic conditions. Biotron 15:61-70

Gislum R, Griffith SM (2004) Tiller production and development in perennial ryegrass in relation to nitrogen use. J plant Nutr 27:2135-2148

Hodge A, Stewart J, Robinson D, Griffiths BS, Fitter AH (2000) Competition between roots and soil micro- organisms for nutrients from nitrogen-rich patches of varying complexity. J Ecol 88:150-164

Houba VJG, Van Der Lee JJ, Novozamsky I, Walinga I (1989) Soil and plant analysis, a series of syllabi, Part 5. Wageningen University, the Netherlands

Jingguo W, Bakken LR (1989) Nitrogen mineralization in rhizosphere and non-rhizosphere soil, effect of the spatial distribution of N-rich and N-poor plant residues. In Hansen JA, Henriksen K (ed) Nitrogen in organic wastes supplied to soils. Academic Press, London, San Diego, pp 81-97

Jonasson S, Castro J, Michelsen A (2006) Interactions between plants, litter and microbes in cycling of nitrogen and phosphorus in the arctic. Soil Biol Biochem 38:526-532

Katterer T, Reichstein M, Anren O, Lomander A (1998) Temperature dependence of organic matter decomposition: A critical review using literature data analyzed with different models. Biol Fertil Soils 27:258–262

Lantinga EA, Gaborcik N, Dirks BOM (1996) Ecophysiological aspects of herbage production in grazed and cut grassland. In: Parente G, Frame J, Orsi S (ed) Grassland and land use systems. Proceedings of the 16th general meeting of the European grassland federation Italy, pp 151-161

Laakso J, Setälä H, Palojärvi J (2000) Influence of decomposer food web structure and nitrogen availability on plant growth. Plant Soil 225:153–165

Liu X, Herbert SJ, Hashemi AM, Zhang X, Ding G (2006) Effects of agricultural management on soil organic matter and carbon transformation–a review. Plant Soil Environ 52:531–543

MAFF (1979) Profitable utilization of livestock manures. ADAS Booklet 2081, HMSO, London

MAFF (1986) The analysis of agricultural materials. Ministry of agriculture fisheries and food, reference Book 427. HMSO, London

Magdoff FR (1978) Influence of manure application rates and continuous corn on soil-N. Agron J 70:629-632

Marcelis LFM, Heuvelink E, Goudriaan J (1998) Modelling biomass production and yield of horticultural crops: a review. Scientia Horti 74:83-111

Mitchell KJ, Coles STJ (1955) Effects of defoliation and shading on short rotation rye-grass. N Z J Sci Tech 36:586-604

Mosier AR, Doran JW, Freney JR (2002) Managing soil denitrification. J Soil Water Conserv 57:505-513

Nebauer SG, Renau-Morata B, Gurdiola JL, Molina RV (2011) Photosynthesis down-regulation preceeds carbohydrate accumulation under sink limitation in Citrus. Tree Physiol 31:169-177

Nieder R, Benbi DK, Scherer HW (2011) Fixation and defixation of ammonium in soils: a review. Biol Fertil Soils 47:1-14

Nommik H, Vahtras K (1982) Retention and fixation of ammonium and ammonia in soils. In: Stevenson FJ (ed) Nitrogen in agricultural soils. Agronomy 22, American Society of Agronomy, Madison pp 123-171

Petersen SO, Nissen HH, Lund I, Ambus P (2003) Redistribution of slurry components as influenced by injection method, soil and slurry properties. J Environ Qual 32:2399-2409

Preusch PL, Alder PR, Sikora LJ, Tworkoski TJ (2002) Nitrogen and phosphorus availability in composted and uncomposted poultry manure. J Environ Qual 31:2051-2057

Schjonning P, Thomsen IK, Moberg JP, de Jonge J, Kristensen K, Christensen BT (1999) Turnover of organic matter in differently textured soils, I: Physical characteristics of structurally disturbed and intact soils. Geoderma 80:177-198

Sharkey MJ (1970) Errors in measuring nitrogen and dry matter content of plant and faeces material. J Brit Grassl Soc 25:289-294

Simon JC, Lemaire G (1987) Tillering and leaf area index in grasses in the vegetative phase. Grass Forage Sci 42:373-380

Sonneveld MPW, Lantinga EA (2010) The contribution of mineralization to grassland N uptake on peatland soils with anthropogenic A horizons. Plant Soil 340:357-368

Sørensen P, Jensen ES (1995a) Mineralization-immobilizing and plant uptake of nitrogen as influenced by the spatial distribution of cattle slurry in soils of different texture. Plant Soil 173:283-291

Sørensen P, Jensen ES (1995b) Mineralization of carbon and nitrogen from fresh and anaerobically stored sheep manure in soils of different texture. Biol Fert Soils 19:29-35

Sørensen P, Jensen ES (1998) The use of ^{15}N labelling to study the turnover and utilization of ruminant manure N. Biol Fertil Soils 28:56-63

Stevenson FJ (1982) Nitrogen in agricultural soils. Agronomy 22, American Society of Agronomy, Madison

Thomas H, Norris JB (1981) The influence of light and temperature during winter on growth and death in simulated swards of *Lolium perenne.* Grass Forage Sci 36:107-116

Thomsen IK, Olesen JE (2000) C and N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. J Agric Sci Cambr 135:151-159

Tyson SC, Cabrera ML (2008) Nitrogen mineralization in soils amended with composted and non-composted poultry litter. Comm Soil Sci Plant Anal 24:2361-2374

Van Veen JA, Kuikman PJ (1990) Soil structure aspects of decomposition of organic matter by micro-organisms. Biogeochemistry 11:213-233

Walker TS, Bais HP, Grotewold E, Vivanco JM (2003) Root exudation and rhizosphere biology. Plant Physiol 132:44-51

Watts DB, Torbert H, Prior SA (2007) Mineralization of nitrogen in soils amended with dairy manure as affected by wetting/drying cycles. Communi Soil Sci Plant Anal 38:2103–2116

Webb J, Pain B, Bittman S, Morgan J (2010) The impacts of manure application methods on emissions of ammonia, nitrous oxides and crop response-A review. Agric Ecosyst Environ 137:39-46

Whitehead DC, Bristow AW, Pain BF (1989) The influence of some cattle and pig slurries on the uptake of nitrogen by ryegrass in relation to fractionation of the slurry N. Plant Soil 117:111-120

Wilson JB (1988) A review of evidence on the control of shoot: root ratio, in relation to models. Ann Bot 61:433-449

Wood CW, Edwards JH (1992) Agroecosystem management effects on soil carbon and nitrogen. Agri Ecosyst Environ 39:123-138

Yang XM, Drury CF, Reynolds WD, Tan CS (2004) Nitrogen mineralization and uptake by ryegrass in a clay loam soil amended with composts or liquid pig manure. Canad J Soil Sci 84:11-17

Chapter 3

Magnitude and routes of nitrogen and carbon losses from solid cattle manure subjected to various storage conditions

G.M. Shah, G.A. Shah, J.C.J. Groot, O. Oenema, E.A. Lantinga

Abstract

The objectives of our study were to quantify the effects of contrasting storage methods of solid cattle manure on: (i) emissions of ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4), (ii) total carbon (C) and nitrogen (N) balances during storage, and (iii) crop apparent N recovery (ANR) following manure application to arable land with maize as test crop. Portions of 10 Mg of fresh solid cattle manure were stored for five months in three replicates as: (i) stockpiled heaps, (ii) roofed heaps, (iii) covered heaps, and (iv) composted heaps. Surface emissions of NH_3, N_2O, CO_2 and CH_4 were measured regularly using a static flux chamber connected to a photoacoustic gas monitor. Total C and N losses during storage were determined through the mass balance method. After storage, the manures were surface-applied and incorporated in a sandy soil, and maize ANR was measured both as a proportion of field applied N (ANR_F) and collected N from the barn (ANR_B).

During the storage period, on average 6% of the initial N_{total} was lost from the covered, 12% from the roofed, 21% from the stockpiled and 33% from the composted heaps. Of the total N losses, 2-9% was lost as NH_3-N, 1-4% as N_2O-N and 16-32% through leaching. However, the greater part of the total N loss from the four storage methods was unaccounted for and constituted in all probability of harmless dinitrogen gas. Of the initial C content, about 13, 14, 17 and 22% was lost from the covered, stockpiled, roofed and composted heaps, respectively. Maize ANR_F was highest from covered (39% of the applied N) followed by roofed (31%), stockpiled (29%) and composted manure (20%). The respective values in case of maize ANR_B were 37, 27, 23 and 13%. It is concluded that from a viewpoint of on-farm N recycling the storage of solid cattle manure under an impermeable plastic cover is much better than traditional stockpiling or composting in the open air.

Keywords: Solid cattle manure, manure storage, ammonia, greenhouse gases, leaching, manure incorporation, maize N recovery

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3.1. Introduction

Ammonia (NH_3) and greenhouse gases like nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) emissions from livestock farming systems are a concern due to their possible/potential adverse environmental effects (Groot Koerkamp 1998; Jeppsson 1999; Amon et al. 2001; Oenema et al. 2005). High NH_3 emission can cause acidification and eutrophication of oligotrophic ecosystems, and enhances deposition of NH_x together with sulphate particles, which may alter the net irradiance among the various atmospheric layers (Sutton and Fowler 2002). Further, it can react with other complex compounds to form particulate matter that may cause haze and reduce natural visibility. The N_2O and CH_4 emissions contribute to global warming by destroying the stratospheric ozone layer (Crutzen 1981). Emission of all these gases may occur in each component of the solid cattle manure management chain, i.e. animal housing, storage and field application, but the highest losses are likely associated with the storage phase (Hutchings et al. 2001).

After excretion in barns, solid cattle manure is directly applied to the field or stockpiled and/or composted in the open air for a certain period of time prior to field application. When uncovered, the stored manure is subjected to ambient environmental conditions (i.e. rainfall, temperature, wind and radiation), which influence gaseous emissions and leaching of nitrogen (N) from the heaps (Kirchmann 1985). These losses may not only contribute to environmental pollution but also reduce the N fertiliser value of manure. Turning of the manure heap during composting exposes the inner fresh material to microbial colonisation which increases the manure decomposition rate and hence the temperature inside the heap. Additionally, the inner voids of the heap are exposed to the air, which will boost gaseous emissions (Amon et al. 2001; Parkinson et al. 2004; Sagoo et al. 2005). Some farmers stockpile solid cattle manure in a roofed building with the aim to protect it against precipitation and therefore to reduce especially leaching losses (Mosquera et al. 2006), however, this is not a common practice. All these storage methods result in substantial gaseous emissions and leaching of N up to about 50% of the initial N content from the heaps (Eghball et al. 1997; Petersen et al. 1998; Shah et al. 2012a).

Several strategies have been proposed to reduce the storage N losses. These include compaction and/or covering of manure heaps, use of chemical as well as biochemical additives, and application of additional straw (Sommer and Møller 2000; Chadwick 2005; Yamulki 2006; Ndegwa et al. 2008; Shah et al. in review). It has been shown that NH_3 emission from solid cattle manure can be reduced by up to 80% through covering the heap with a tarpaulin sheet with respect to an uncovered control (Sagoo et al. 2007). Chadwick (2005) reported that compaction and subsequent covering of a manure heap can reduce NH_3 and N_2O emissions by about 90 and 30%, respectively. Application of chemical and biochemical additives has the potential to reduce NH_3 emissions by even up to 100% (Ndegwa et al. 2008). Application of additional straw to solid manure reduced N_2O emission by 57% compared to the heap without additional straw (Yamulki 2006). However, straw addition might increase dry matter (DM) and NH_3 losses by promoting aerobic conditions inside the heap (Kirchmann 1985). Despite all these efforts, there are still large uncertainties in the emission estimates from the basket of storage methods whilst the routes of N loss are not well quantified yet.

Storage conditions not only affect the level of N losses but also determine the characteristics of the end product, which can be decisive for subsequent N release for crop uptake after manure application (Kirchmann 1985; Shah et al. 2012a; Rashid et al. 2012). Anaerobic storage results in the production of low molecular compounds i.e. volatile fatty acids, alcohols and phenols, and higher contents of NH_4^+-N (Kirchmann 1985; Thomsen and Olesen 2000). Composting transforms a part of the easily degradable N leading to the formation of stable N compounds with a relatively low C/N ratio. Consequently, microbial decomposition and mineralisation activities after application of composted manure to soil will be lower as compared to anaerobically stored manure. For instance, Shah et al. (2012a) found a 35% higher plant N utilisation from the latter manure type during the year of application. Thus, it will be worthwhile to examine also the crop N recovery and DM yield from stored manure for a better evaluation of the storage methods.

The objectives of this study were therefore to quantify the effects of contrasting storage methods of solid cattle manure on (i) emissions of NH_3, N_2O, CO_2 and CH_4, (ii) C and N balances during storage, and (iii) apparent N recovery from both field applied N (ANR_F) and collected N from the barn (ANR_B), after application to maize cropped land.

3.2. Materials and methods

3.2.1. Storage treatments

Fresh solid cattle manure was collected from a naturally ventilated sloping-floor litter-barn with young beef cattle, where chopped cereal straw was used as bedding material at a daily rate of 5 kg per livestock unit. Immediately thereafter, portions of 10 Mg manure were put on a clean concrete floor to make conical heaps with a height of about 1.5 m and a base diameter of about 5 m. There were four manure storage methods: (i) stockpiled heap in the open air, (ii) roofed heap: stockpiled heap under a plastic roof, (iii) covered heap: stockpiled heap covered with an impermeable plastic sheet, and (iv) composted heap with monthly turnings. All the treatments were arranged in a randomised complete block design with three replicates. The manure heaps were build-up in bunkers bounded by one course of concrete blocks around three sides (approximately 0.5 m high) and a ridge of sand forming the fourth side (30 cm high). In this way leachates could be collected and it facilitated the access of a tractor with front end-loader for the turning operations in case of the composted heaps. For each of the covered heaps, an impermeable plastic sheet (0.15 mm thick polyethylene film) was used which was lined at its bottom and at the top. The edges of the plastic sheet were covered with sand-filled plastic sacks in order to block the inflow of air into the heap. For each roofed heap, an artificial roof was built by mounting a thick impermeable plastic sheet (0.15 mm thick polyethylene film) on four curved iron posts each with a height of 4 m in the middle. The manure was stored for 160 days starting from the 1st week of December 2009 until the 2nd week of May 2010.

3.2.2. Manure sampling and analyses

Both at the start and end of the storage period, three manure composite samples (ca. 2 kg fresh wt.) were collected from each heap. Each composite sample consisted of 20-30 sub-samples taken by hand from different locations of a heap. The samples were stored at -18°C until analysis in order to prevent N transformations. Before analysis, the samples were thawed at room temperature (20°C) and subsequently chopped with a cutting machine in order to cut straw particles into small pieces (≤ 2 cm) (Sommer and Dahl 1999). From this material, representative sub-samples of about 100 g were analysed for total N, NH_4^+-N, nitrate-N (NO_3^--N), pH, DM and raw ash (Table 3.1). Total N was measured after Kjeldahl digestion (MAFF 1986). Contents of NH_4-N and NO_3-N were measured in a 1:10 manure/0.01 M $CaCl_2$ extract by means of segmented-flow analysis (Houba et al. 1989). The pH was measured in the same extract using a pH meter (inoLab pH meter level 1, WTW GmbH & Co. KG, Germany). DM was determined after drying the samples at 105°C for 24 hours (Anonymous 1998).

Table 3.1. Chemical composition of solid cattle manure (means and standard errors; n = 3) at the start and end of the storage period.

Sampling occasion	Treatments	DM (%)	Ash	C_{total}	N_{total}	$N_{min.}$	$N_{min.}/N_{total}$ (%)	C/N ratio	pH-$CaCl_2$‡
			(g kg^{-1}DM)						
Initial	Roofed	21.7±0.5	287±4.5	357±2.2	29.7±0.7	4.1±0.4	14	12.0±0.3	8.0
	Stockpiled	21.3±0.5	291±3.1	355±1.6	31.2±1.7	4.2±0.3	14	11.4±0.6	8.0
	Composted	21.4±0.7	301±13	349±6.5	32.5±2.5	4.7±0.3	15	10.9±1.1	8.1
	Covered	21.7±0.3	280±4.7	360±2.3	29.8±0.3	3.6±0.1	12	12.1±0.2	8.0
Final	Roofed	21.1±0.0	324±9.5	338±4.8	29.7±0.4	4.2±0.5	14	11.4±0.0	8.1
	Stockpiled	21.2±0.3	323±4.9	339±2.4	27.3±1.1	2.9±0.2	10	12.4±0.4	8.1
	Composted	22.2±0.3	321±7.8	339±3.9	27.2±1.4	2.2±0.2	9	12.5±0.6	8.3
	Covered	20.5±0.2	320±6.5	340±3.3	30.4±0.4	5.1±0.3	17	11.2±0.2	7.8

‡ standard errors < 0.1.

Subsequently, raw ash content was determined gravimetrically through ignition of the dried samples at 525°C for 6 hours (Anonymous 1998) with organic matter (OM) being equal to the ignition losses. Total C was assumed to be 50% of the OM (Pettygrove et al. 2009).

3.2.3. Measurement of gaseous concentrations and calculation of their fluxes

Fluxes of NH_3, N_2O, CO_2 and CH_4 from the surface of manure heaps were quantified using a static flux chamber connected to a photoacoustic gas monitor (INNOVA 1412A, LumaSense Technologies, Ballerup, Denmark; Predotova et al. 2010) by two Teflon tubes (internal diameter = 3 mm) each of 1.5 m long. The tubes were made of polyvinyl chloride (PVC), which is known to have low NH_3 adsorption capacity (Shah et al. 2006). The gas monitor had a built-in pump for recirculation of gases in the flux chamber. The flux chamber had a sharp bottom edge and an internal diameter of 0.3 m. The total internal volume of the chamber was 2.12×10^{-2} m^3. The measurements were done on daily to bi-weekly intervals. At each measurement event, the flux chamber was gently pressed down 4 cm deep into the surface of manure heap. Thereafter, time patterns of NH_3, N_2O, CO_2 and CH_4 concentrations were recorded for 10 minutes. Measurements were made from three random places of the roofed, stockpiled and composted heaps on 20 different days during the storage period. These measurements were not possible from the covered heaps. The photoacoustic gas monitor was calibrated by its manufacturer company (ENMO, Vosselaar, Belgium) and had built-in compensation for cross-interferences of CO_2 and water vapour with NH_3, N_2O and CH_4. The calibration was done in April 2009 and May 2010, and the monitor was found to be in well-performing condition on both occasions. However, during validation sessions for the above measuring set up, Predotova et al. (2010) found average errors for NH_3, N_2O, CO_2 and CH_4 of -13, -12, 5 and -2%, respectively, resulting in possible slight underestimation of N losses.

Instantaneous emission rates of NH_3, N_2O, CO_2 or CH_4 were calculated from the fitted (linear) slope of gas concentration (mg m^{-3}) versus time (minutes). Small negative emission rates that occasionally occurred especially at the end of the storage period were set to zero. The gaseous emission rates (R) for the manure heap in units of mg m^{-2} h^{-1} were calculated as

$$R = 60 \times B_i \frac{V_T}{A_C} \qquad (3.1)$$

Where 60 is the conversion factor for up-scaling mg min^{-1} to mg h^{-1}, B_i is the fitted linear slope of the data between NH_3, N_2O, CO_2 or CH_4 concentrations and time (mg m^{-3} min^{-1}), V_T is the total volume of the air inside the monitoring system during measurement (1.82×10^{-2} m^3) and A_c is the surface area of the solid manure heap covered by the flux chamber (7.07×10^{-2} m^2). V_T was calculated by subtracting the reduced volume of the flux chamber (after inserting into the solid manure heap) (3.18×10^{-3} m^3) from the total internal volume of the chamber (2.12×10^{-2} m^3) and subsequently adding the internal volume of the PVC tubes (1.41×10^{-5} m^3) and the air volume inside the gas monitor (1.4×10^{-4} m^3).

Emission totals for NH_3-N, N_2O-N, CO_2-C and CH_4-C were calculated by averaging the emission rates between two consecutive sampling dates and multiplying with the time elapsed between these two points (e.g. Chadwick 2005; Moral et al. 2012). The emissions were upscaled from mg m^{-2} to kg heap^{-1} by multiplying it with the surface area of the heaps, which was measured periodically during the storage period. Subsequently, the emission values were summed for the whole storage period.

Finally, the N losses unaccounted for (UNL) as a proportion of the established total N losses (TNL in kg heap^{-1}) were calculated by

$$\text{UNL (\% of total losses)} = 100 \times \frac{(\text{TNL} - \text{NH}_3\text{-N} - \text{N}_2\text{O-N} - \text{N leached})}{\text{TNL}} \tag{3.2}$$

The C losses unaccounted for (UCL) as a proportion of the established total C losses (TCL in kg heap^{-1}) were calculated by

$$\text{UCL (\% of total losses)} = 100 \times \frac{(\text{TCL} - \text{CO}_2\text{-C} - \text{CH}_4\text{-C} - \text{C leached})}{\text{TCL}} \tag{3.3}$$

3.2.4. Collection of leachates

The concrete floor of each bunker sloped towards one side to facilitate the collection of effluent in the adjacent concrete collection tanks. The tanks, each measuring 5 m * 1 m * 1.5 m, were constructed under the soil surface and covered with concrete blocks to avoid the direct addition of rain water. From each individual tank, leachates were collected four times throughout the whole storage period and the total volume was measured. To this end, leachates were mechanically stirred and representative samples of about 1 litre per tank were taken. Thereafter, the samples were analysed for total N, NO_3^--N, NH_4^+-N, C, DM and ash content according to the procedures as described in section 3.2.2.

3.2.5. Temperature and precipitation measurements

Throughout the storage period, heap temperatures were automatically recorded with 1 hour intervals at depths of 0.5 m (surface), 1.0 m (middle) and 1.5 m (bottom) using thermocouples connected with a data logger (Datataker DT 200, Data electronics Ltd, Australia; Fig. 3.1). The thermocouples were permanently inserted in the stockpiled, roofed and covered heaps, whereas in case of the composted heaps these were removed just before a turning event and inserted back thereafter in the respective layers. Three thermocouples were left outside in the open air in order to measure the ambient temperature at 0.5 m height. Precipitation was measured during the whole experimental period with a rain gauge in the experimental area.

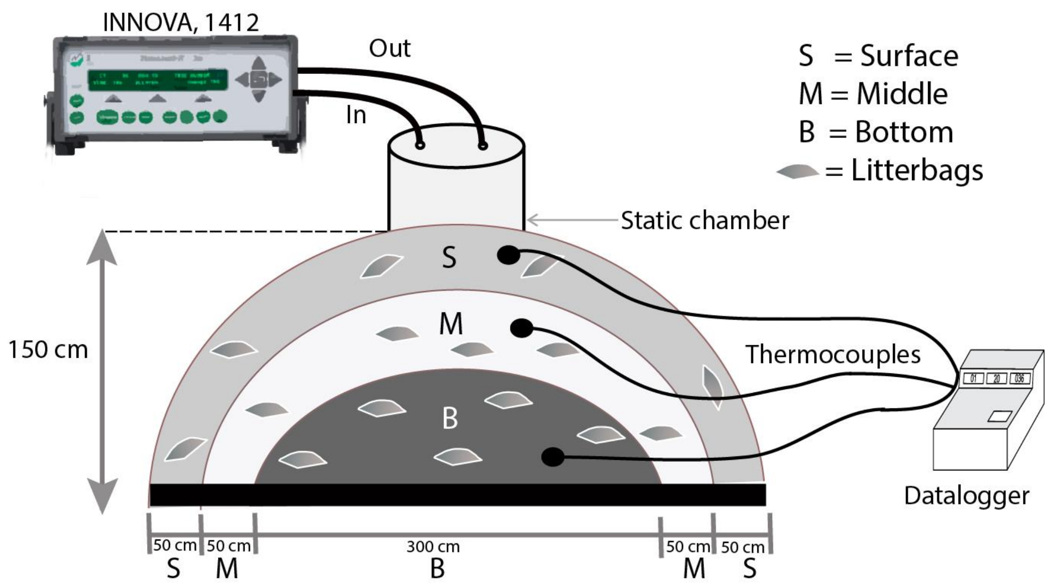

Fig. 3.1. Schematic diagram of cross section of a manure heap.

3.2.6. Mass balance through litterbag technique

For each heap, a total of fifteen litterbags, each measuring 10 cm * 10 cm and made of nylon with 1 mm mesh, were filled with 100 g of fresh solid cattle manure. After filling, they were firmly closed with long nylon strings and placed at three layers (surface, middle and bottom) of each heap, i.e. randomly 5 litterbags per layer (Fig. 3.1). One end of the string was marked with a non-decomposable tag and was kept outside the heap in order to distinguish among the layers. In the composted heap, all the litterbags were removed just before turning and placed back thereafter in the respective layers. At the end of the storage period, litterbags from all heaps were collected carefully and the leftover materials were weighed and analysed for total N, NH_4^+-N, NO_3^--N, DM, total C and raw ash according to the procedures described earlier in section 3.2.2. Thereafter, total DM, C and N losses were calculated through the mass balance method.

3.2.7. Crop N recovery

After the storage phase, all the stored manures together with fresh manure taken directly from the barn (total N 29.7 g kg^{-1} DM, mineral N 3.7 g kg^{-1} DM and C/N ratio 12) were incorporated in the top layer of a sandy farm field at an application rate of 170 kg N ha^{-1}. Treatments comprised: (i) control (unfertilised), (ii) fresh manure, (iii) stockpiled manure, (iv) roofed manure, (v) covered manure, and (vi) composted manure. All the treatments were arranged in a randomised complete block design with four replicates. The plot size was 15 m × 4.5 m. One week after manure incorporation (on May 19, 2010), maize seeds (cultivar: Lapriora) were sown at 6 cm depth and a density of 11 plants m^{-2}. In each plot, there were 6 rows of maize plants with a row spacing of 75 cm. The experimental area was weeded manually during its vegetative growth period. Maize was harvested at the beginning of grain filling to estimate aboveground N uptake and DM yield. Around this phenological development stage, i.e. before leaf senescence starts, total N contents of field-grown maize plants reach their peak value (Shah et al. in review). For this purpose, randomly 10 plants from the inner rows were cut to ground level and the actual number of plants per plot was counted. Thereafter, fresh maize biomass was measured in the field and subsequently chopped with a cutting machine in order to take representative fresh samples of about 500 g. Subsequently, the samples were oven-dried at 70°C for 48 hours, ground to pass 1 mm sieve and analysed for total N content through Kjeldahl digestion (MAFF 1986). Maize apparent N recovery in the field (ANR_F) was calculated as

$$\mathrm{ANR_F}\ (\%) = \frac{(\mathrm{N_m} \times \mathrm{DM_m}) - (\mathrm{N_0} \times \mathrm{DM_0})}{\mathrm{TN_a}} \times 100 \qquad (3.4)$$

Where N_m is maize N content (mg N (kg DM)$^{-1}$) in the manured plots, DM_m is maize DM yield (kg ha^{-1}) in the manured plots, N_0 is maize N content (mg N (kg DM)$^{-1}$) in the unfertilised plots, DM_0 is maize DM yield (kg ha^{-1}) in the unfertilised plots and TN_a is total N applied with manure (kg ha^{-1}).

Thereafter, apparent maize N recovery of the N collected from the barn (ANR_B) was calculated as

$$\mathrm{ANR_B}\ (\%) = \frac{(\mathrm{TN_{barn}} - \mathrm{TNloss_{storage}}) \times \mathrm{ANR_F}}{\mathrm{TN_{barn}}} \times 100 \qquad (3.5)$$

Where TN_{barn} is total amount of manure N taken from the barn (kg), $TNloss_{storage}$ is total N lost during storage (kg) and ANR_F is apparent maize N recovery in the field (%).

3.2.8. Statistical analysis

The measurements for emissions of NH_3, N_2O, CH_4 and CO_2, N leaching and mass balances (DM, C and N) through litterbags were restricted to only one replication because of practical constraints. Emissions of NH_3, N_2O, CO_2 and CH_4 determined at three random places of each manure heap were averaged per heap and measurement event. Thereafter, mean values were statistically analysed using analysis of variance (ANOVA) in Genstat (13th Edition, VSN International, Hemel Hempstead, UK). For this purpose, storage methods (n = 4) were taken as treatments and days of measurement (n = 20) as replicates. Results from the litterbag measurements were statistically analysed by considering the five litterbags in each layer of a heap as replicates.

Total DM, C and N losses from the heaps during storage, and maize crop N recovery after manure application in the arable field were statistically analysed using ANOVA in Genstat. When the overall main effects were significant ($P < 0.05$), differences among treatments were further compared using a Duncan's multiple range test for all variables.

3.3. Results

3.3.1. Total DM, C and N losses

Mass balances revealed that highest total DM, C and N losses occurred in the composted heaps and were lowest in the covered heaps (Tables 3.2 and 3.3; $P < 0.05$). On average, 10% of the initial DM from the stockpiled, 12% from the roofed, 8% from the covered and 20% from the composted heaps were lost. The respective values for total C losses were 14, 17, 13 and 22% (Table 3.2). About

21% of the initial N_{total} was lost from the stockpiled heap, whereas this fraction was 12% from the roofed, 6% from the covered and 33% from the composted heaps (Table 3.3). Total DM, C and N losses (% of initial) from the litterbags (Tables 3.4) were in line with their respective values derived from the mass balance at heap level (Table 3.4 vs. Tables 3.2 and 3.3). Overall, both DM and C losses were higher ($P < 0.05$) from the surface layer of the roofed heap in comparison with the other two layers. However, there was no difference among the three layers of the stockpiled, composted and covered heaps (Table 3.4). Among the layers N losses (% of initial) were higher ($P < 0.05$) from the surface layer of the stockpiled heap while these were lower ($P < 0.05$) from the bottom layer of the roofed heap as compared to the two other layers. In case of the composted and covered heaps there appeared to be no differences (Table 3.4; $P > 0.05$).

3.3.2. Gaseous emissions and unaccounted losses

Emissions of NH_3, CO_2 and CH_4 peaked a few days after heap establishment and gradually declined thereafter. These patterns were closely correlated with the temperature decrease during the winter period (Fig. 3.2). The CO_2 emissions were lower from the stockpiled heap than from the roofed and composted heaps ($P < 0.05$; Fig. 3.3a). In the composting treatment, CO_2 losses were increased after each turning event, especially at day-127. During the first two weeks of the storage period, CH_4 emissions from the roofed heap were about three times higher than from the composted and stockpiled heaps (Fig. 3.3b). After this initial storage phase, there were only small differences among these three heap types. Over the whole storage period, total measured gaseous and liquid C losses were about 39, 59 and 70% of the total C losses from the stockpiled, composted and roofed heaps, respectively (Table 3.2). The respective shares of total CO_2-C and CH_4-C emissions together in these measured losses were 68, 84 and 97%, while the remainder was lost through C leaching. Overall, about 61% of the total C losses from the stockpiled, 41% from the composted and 30% from the roofed heaps were thus unaccounted for (Table 3.2).

Emissions of NH_3 increased after each turning event in case of the composted heaps especially at the last turning event (Fig. 3.3c). In case of the stockpiled heaps, NH_3 emissions dropped down to values close to zero within 10 days after heap establishment. Similarly, N_2O emissions were only marginal after one week of heap establishment from the stockpiled treatment until day-100 (Fig. 3.3d). Consequently, the measured total N_2O-N emissions from the stockpiled heap were about 2 to 4 times lower as compared to the composted and

Table 3.2. Summary of dry matter (DM) and carbon (C) balances for solid cattle manure stored under different conditions (n = 3). Values in the parenthesis are the percentages of the initial amount.

Treatment	DM balance			C balance									
	Initial	Final	Difference	Initial	Final	Difference	CH_4-C emission	CO_2-C emission	Total C leached	Measured C losses		Unaccounted C losses	
	(kg heap^{-1})									kg heap^{-1}	% of total C losses	kg heap^{-1}	% of total C losses
Roofed	2125	1871	$254^{a\dagger}$ (12)	758	633	125^{ab} (17)	12	72	3	§87	70	‖38	30
Stockpiled	2097	1895	202^{a} (10)	744	642	102^{a} (14)	9	18	13	40	39	62	61
Composted	2298	1843	455^{b} (20)	803	625	178^{b} (22)	15	73	17	105	59	73	41
Covered	2270	2095	175^{a} (8)	818	713	105^{a} (13)	N/A‡	N/A	2	2	2	103	98

† The means within a column followed by different letters as superscript are significantly different ($P < 0.05$) from each other

‡ not applicable

§ Measured C losses (kg heap^{-1}) = (CO_2-C + CH_4-C + Total C leached);

‖ Unaccounted C losses (kg heap^{-1}) = (Initial total C − Final total C) − measured C losses

Table 3.3. Summary of nitrogen (N) balance for solid cattle manure stored under different conditions (n = 3). Values in the parenthesis are percentages of the intitial amount.

Treatment	Initial	Final	Difference	Total NH_3-N emission	Total N_2O-N emission	Total N leached	Measured N losses		Unaccounted N losses	
	(kg heap^{-1})						kg heap^{-1}	% of total N losses	kg heap^{-1}	% of total N losses
Roofed	63.1	55.5	7.6^{ab}† (12)	0.67	0.32	1.2	§ 2.2	28	‖ 5.4	72
Stockpiled	65.3	51.8	13.5^{b} (21)	0.26	0.07	3.2	3.5	26	10.0	74
Composted	74.7	50.3	24.4^{c} (33)	0.77	0.14	3.8	4.7	19	19.7	81
Covered	67.7	63.6	4.1^{a} (6)	N/A‡	N/A	1.3	1.3	32	2.8	68

† The means within a column followed by different letters as superscript are significantly different ($P < 0.05$) from each other
‡ not applicable
§ Measured N losses (kg heap^{-1}) = (NH_3-N + N_2O-N + Total N leached)
‖ Unaccounted N losses (kg heap^{-1}) = (Initial total N − Final total N) − measured N losses

Table 3.4. Dry matter (DM), carbon (C) and nitrogen (N) balances of litterbags placed in the surface, middle and bottom layers of the solid cattle manure heaps (n = 5).

	DM losses (% of initial)				C losses (% of initial)				N losses (% of initial)			
Layers	Roofed	Stockpiled	Composted	Covered	Roofed	Stockpiled	Composted	Covered	Roofed	Stockpiled	Composted	Covered
Surface	15^{a}†	10^{a}	12^{a}	12^{a}	21^{a}	15^{a}	17^{a}	16^{a}	17^{a}	27^{a}	28^{a}	6^{a}
Middle	4^{b}	12^{a}	9^{a}	9^{a}	5^{b}	17^{a}	12^{a}	13^{a}	17^{a}	12^{b}	25^{a}	7^{a}
Bottom	5^{b}	8^{a}	11^{a}	11^{a}	7^{b}	12^{a}	16^{a}	15^{a}	1^{b}	8^{b}	30^{a}	6^{a}

† The means within a column followed by different letters as superscript are significantly different ($P < 0.05$) from each other.

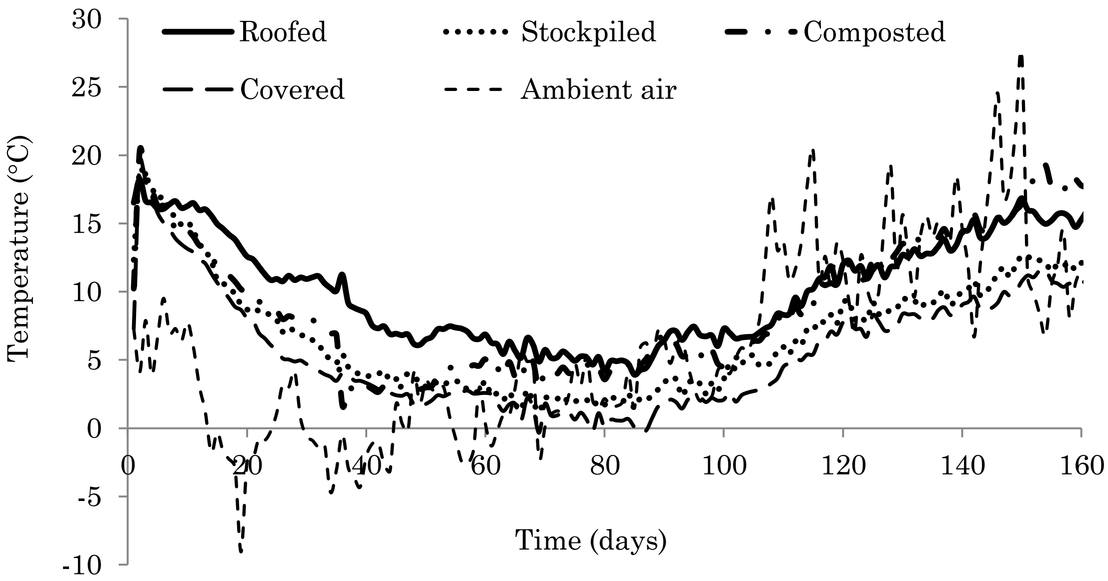

Fig. 3.2. Average temperature inside the manure heaps during the storage period.

roofed heaps (Table 3.3). N leaching from the stockpiled and composted heaps was about three times higher than from the covered or roofed heaps (Table 3.3). Of the total measured gaseous and liquid N losses together, the cumulative emissions of NH_3-N and N_2O-N were only 9% from the stockpiled, 19% from the composted and 45% from the roofed heaps. The respective N leaching losses constituted 91, 81 and 55%. From the covered heap all measured N losses refer to leaching processes (32% of total N losses) as gaseous emissions could not be measured. On average, 74% of the total storage N losses from all of the manure heaps subjected to various storage conditions could not be accounted for. These unaccounted losses were highest (81% of total N losses) for the composted and lowest (68%) for the covered heaps, whereas the roofed and stockpiled heaps took an intermediate position with respective values of 72 and 74% (Table 3.3).

3.3.3. Temperature inside the heaps

Temperature inside the manure heaps initially increased to about 20°C, subsequently decreased and after day-100 it increased again (Fig. 3.2). On average, temperature was higher in the roofed and composted heaps as compared to the stockpiled and covered heaps. For each storage treatment, there was only a slight difference among the heap layers; therefore, only the temperature pattern over time from the middle layer is presented in Fig. 3.2.

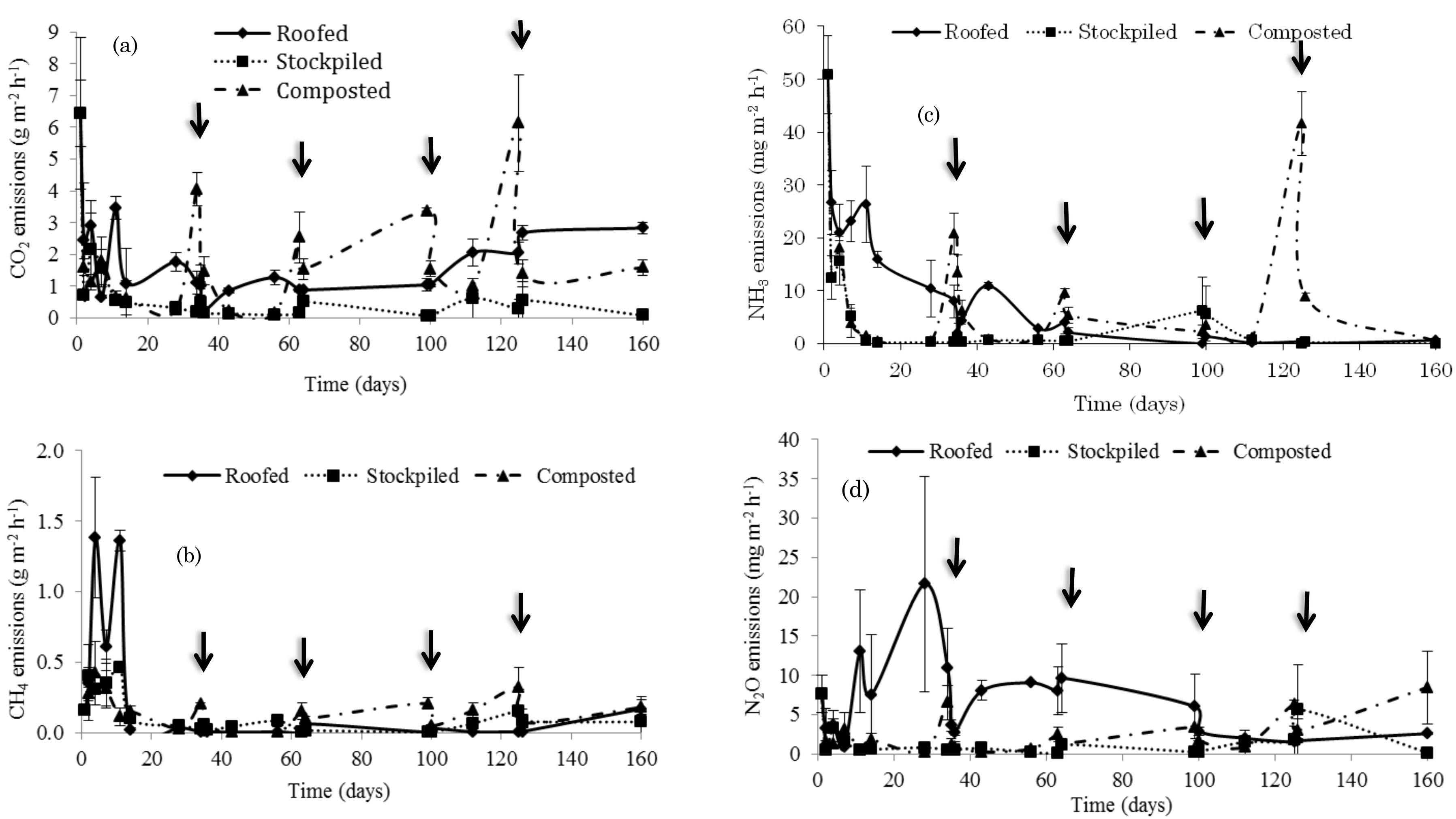

Fig. 3.3. Emissions of (a) CO_2, (b) CH_4, (c) NH_3 and (d) N_2O over time from the manure heap surface during the storage period. Error bars represent standard errors (±) of the mean and arrows show manure turning events for the composted heaps.

3.3.4. Crop N recovery

Maize DM yield, N uptake, ANR_F and ANR_B are presented in Table 3.5. Type of manure storage method had a great impact on all of these parameters. Values of ANR_F were highest from covered manure and lowest in case of composted manure (39 vs. 20% of the applied N; $P < 0.05$). Moreover, an almost three times higher ANR_B value was found from covered compared to composted manure (37 vs. 13%, Table 3.5). For both of these ANR parameters, there was no difference among stockpiled, roofed and fresh manures (Table 3.5; $P > 0.05$). Finally, the storage methods did not have an influence on crop N use efficiency (expressed as kg DM (kg N uptake)$^{-1}$), since treatment differences in DM yield were absent at a given level of N uptake (Table 3.5).

Table 3.5. Average (n = 4) maize apparent N recovery from solid cattle manures expressed as fraction of total N applied to the field (ANR_F) and as fraction of total N taken from the barn (ANR_B).

Treatment	DM yield	N uptake	ANR_F	ANR_B	NUE
	(kg ha^{-1})		(%)		(kg DM (kg N uptake)$^{-1}$)
Control	$11155^{d\dagger}$	155^{d}			72^{a}
Fresh	14404^{bc}	204^{b}	28^{b}	28^{b}	71^{a}
Roofed	14738^{bc}	208^{b}	31^{b}	27^{b}	71^{a}
Stockpiled	15513^{ab}	205^{b}	29^{b}	23^{b}	76^{a}
Composted	13554^{c}	190^{c}	20^{c}	13^{c}	72^{a}
Covered	16429^{a}	222^{a}	39^{a}	37^{a}	74^{a}

† The means within a column followed by different letters as superscript are significantly different ($P < 0.05$) from each other.

3.4. Discussion

3.4.1. Total DM and C losses during storage of solid cattle manure

Solid cattle manure is subjected to microbial transformations, chemical reactions and natural drainage during the storage period, which results in losses of moisture, DM and nutrients (Chadwick 2005). In our experiment all the heaps had decreased in size noticeably at the end of the storage period. DM losses were larger from the composted heaps than from the other treatments (Table 3.2). The emission rates of both CO_2 and CH_4 were higher during the first two weeks after heap establishment, declined thereafter and increased again towards the end, coinciding with the patterns of heap temperature (Fig. 3.2).

Total CH_4-C emissions were in the order of 1 to 2% of the initial C content (Table 3.2) and fell in the range of 0.4 to 9.7% of the initial C during storage of solid beef cattle manure as established by Chadwick (2005). Total emissions of CO_2-C were just over 2 to 10% of the initial C, with the smallest losses occurring from the stockpiled heaps. From all treatments, the measured C losses (CH_4-C, CO_2-C and leaching) were on average 54% of total C losses determined through the mass balance method (Table 3.2). This relatively low proportion might partly be explained by errors in the estimates of total CH_4-C and CO_2-C emissions (i.e. unmeasured gaseous emission during turning operations) as their cumulative figures were calculated from a number of measurements at discrete points rather than continuous measurement (e.g. Chadwick 2005, Moral et al. 2012). However, there might have been other unmeasured gaseous C losses involved like non-methane volatile organic compounds (Misselbrook et al. 2011) and carbon monoxide (Hellebrand and Kalk 2001).

Total storage C losses from stockpiled and/or composted heaps in our experiment were lower compared to a number of other studies (Sommer and Dahl 1999; Larney et al. 2006). This could be explained by the relatively cold winter with freezing temperatures as reflected in the measured ambient air temperatures (Fig. 3.2). However, the losses established by us are corroborated with Moral et al. (2012) who also found lower C losses due to heavy rainfall and low temperatures. In our study the ambient temperature dropped below zero after two weeks of heap establishment followed by a freezing period of about 40 days (Fig. 3.2). In spite of the severe winter, storage methods had a significant effect on DM and C losses with highest values in case of the composted heaps. In all probability, this was associated with a higher level of aerobic decomposition as a result from diffusion of air into the straw-based heaps through the turning operations (Parkinson et al. 2004). The heat derived from these aerobic decomposition processes increases temperature inside manure heaps (Hansen et al. 2006). On the contrary, covering of manure blocks air circulation in the heap and thus creates anaerobic conditions. Anaerobic degradation of organic matter restricts microbial activities and does not increase temperature which ultimately reduces the overall loss of C (Hansen et al. 2006).

3.4.2. N losses during storage of solid cattle manure

The total established losses of 21 and 33% of the initial N from the stockpiled and composted heaps in our experiment are in line with Parkinson et al. (2004). Covered storage reduced these N losses by about a factor five. Consequently, mineral N content in covered manure at the end of the storage period was greatly increased (Table 3.1). This increase is important from an agronomical viewpoint especially in case of organic agricultural practices where the use of artificial fertiliser is prohibited. However, due to both the increased mineral N content and pH of covered manure, compensatory losses may occur through increased NH_3 emissions after its land application, when left untreated (e.g. Amon et al. 1997 and 2001). Benefits of manure covering can be maximised through soil incorporation (Webb et al. 2012), irrigation or using additives like lava meal which adsorb ammonium (Shah et al. 2012b).

Measured NH_3-N emission rates were between 0.4 and 1.1% of the initial total N from all of the heaps (Table 3.3), which fell in the range of 0.3 to 4.5% of initial N as reported in the literature (Petersen et al. 1998; Sommer and Dahl 1999; Chadwick 2005; Moral et al. 2012). The NH_3 emission was higher from the roofed and composted heaps compared to the stockpiled heap in the open air (Table 3.3). In case of the composted heaps, turning increased air exchange through the materials and stimulated aerobic decomposition processes which will stimulate the process of NH_3 emission (Amon et al. 2001; Parkinson et al. 2004). Visual observations during the experimental work revealed that the surface of the roofed heaps remained open and porous, especially during the first month of the storage, allowing NH_3 to diffuse easily into the atmosphere. On the other hand, the stockpiled heaps in the open air were subjected to the exposure of weather (wetting and drying), which lead to the formation of a surface crust and thereby creating a physical barrier to gaseous N emissions.

Covering manure heaps with an impermeable sheet inherently blocks air circulation and therefore forms a physical barrier which prevents NH_3 diffusion to the atmosphere (Kirchmann 1985; Hansen et al. 2006). Further, the formation of nitrate and nitrite is restricted under anaerobic conditions and thereby also the occurrence of denitrification losses (Kirchmann 1985). However, leaching losses are unavoidable because of natural seepage since compaction displaces effluents including nutrients out of the heap (Chadwick 2005).

Of the total storage N losses from all treatments, about 2 to 9% was lost as NH_3-N, 1 to 4% as N_2O-N and 16 to 32% through leaching. Between 68 and 81% of the total N losses were unaccounted for. These are in the range of 38 to 92% of total N losses from solid cattle manure storage as observed by Sommer and Dahl (1999). The relatively low fraction of N losses accounted for in our experiment might be partly explained by errors in the emission estimates (i.e. emissions during turning operations were not measured) since the cumulative figures were derived from a number of measurements at discrete points rather than continuous measurements (e.g. Chadwick 2005; Moral et al. 2012). However, by far the greater part of these unaccounted N losses occurred in all probability in the form of the harmless dinitrogen gas, which is the end-product of denitrification (Petersen et al. 1998; Harper et al. 2000; Chadwick 2005).

In case of the composted and stockpiled heaps, N leaching was much higher with regard to the total of NH_3-N and N_2O-N emissions and could be attributed to the high rainfall amounts especially during the month of heap establishment (Fig. 3.4). Turning of manure heaps further increased the leaching processes likely by loosening the heaps, which facilitated the water infiltration from rain and thereby the N leaching from the heap. Leaching losses were remarkably reduced (> 60%) by protection from rain in case of the roofed and covered heaps. Due to relatively high rainfall amount during the first month after heap establishment, N leaching losses were more pronounced in this period than later on. In all probability this was also affected by the depletion of the leachable N pool. During the first three months after heap establishment, N in the leachate was mainly in the form of NH_4^+-N and leachable organic N. Occurrence of NO_3-N, comprising in the leachates only appeared in the month of April following a period of dry weather, which constituted only 2-7% of the total

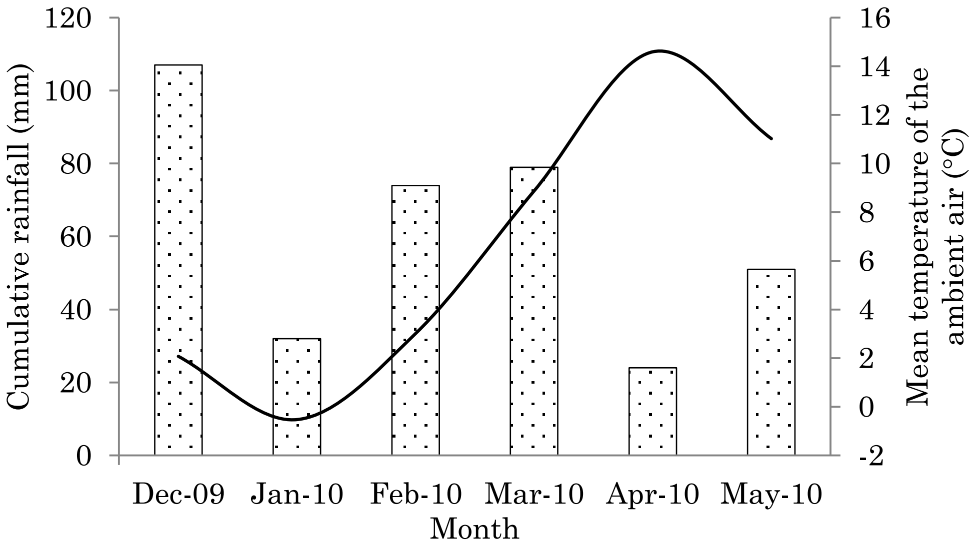

Fig. 3.4. Cumulative rainfall (bars) and mean ambient air temperature (line) during the storage period.

N leaching. The near absence of NO_3-N is in line with previous observations from stockpiled and composted solid cattle manure heaps (Martin and Devis 1992; Eghball et al. 1997; Petersen et al. 1998).

3.4.3. Crop N recovery

After field application, maize ANR_F was lower from composted manure as compared to covered, stockpiled, roofed or fresh manure. The reasons for this appeared to be the (i) relatively greater loss of readily degradable N compounds already during composting resulting in lower mineral N contents, and (ii) conversion of a part of the remaining N into chemical forms that are more stable than those originally present before composting (Kirchmann 1985; Levi- Minzi et al. 1986: Kirchman and Witter 1989; Thomsen 2001). When losses during storage were included in the calculations to arrive at an apparent N recovery for the whole manure handling chain with the barn as starting point (ANR_B), a considerably lower value was observed for composted than for stockpiled, roofed, fresh and covered manures (ANR_B = 13 vs. 23, 27, 28 and 37%, respectively). Interestingly, despite an observed 6% loss of the initial total N during the covered storage, ANR_F from covered manure was higher than from fresh manure taken directly from the barn. This clearly indicates that a significant fraction of the initial organic N was mineralised. Consequently, total mineral N increased by 41% after covered storage with respect to fresh manure (Table 3.1) and thereby increased the N fertiliser value of this currently underutilised manure storage practice.

3.5. Conclusions

This study revealed that C and N losses during storage of solid cattle manure can be reduced considerably by covering the heaps with an impermeable sheet. As an average over all storage treatments, only about one fourth of the total established N losses through the mass balance method could be traced back as gaseous (NH_3 and N_2O) emissions and N leaching losses. The remainder was unaccounted for and constituted in all probability of harmless N_2 gas. Of the measured N losses, highest contribution came from leaching processes and these were about threefold higher from the composted and stockpiled heaps compared to covered storage. After field application, covered manure substantially increased maize crop N recovery and DM yield, especially with regard to composted manure. All these findings lead us to conclude that covered storage is a promising means for helping to retain as much of the animal excreted N in the solid cattle manure management chain. Currently, there are no formal regulations for covering solid manure heaps, while they exist for liquid and slurry manures in countries like the Netherlands and Denmark. The results of this study warrant the need to introduce such kind of regulation also for solid manures.

3.6. Acknowledgments

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3.7. References

Amon B, Amon TT, Boxberger J, Alt C (2001) Emissions of NH3, N2O and CH4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutr Cycl Agroecosyst 60 (1-3):103-113

Amon B, Boxberger J, Amon TH, Zaussinger A, Pollinger A (1997) Emission data of NH3, CH4 and N2O from fattening bulls, milking cows, and during different ways of storing solid manure. In: Amon B, Boxberger J, Amon TH, Zaussinger A, Pollinger A (eds) Ammonia and odour control from animal production facilities. Elsevier, Amsterdam, the Netherlands, pp 397-404

Anonymous (1998) NEN 7432 Manure and derivatives: Determination of the contents of dry matter and organic matter (in Dutch). Gravimetric method. Dutch Standardization Institute (NNI), Delft, the Netherlands,

Chadwick DR (2005) Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: Effect of compaction and covering. Atmos Environ 39 (4):787-799

Crutzen PJ (1981) Atmospheric chemical processes of the oxides of nitrogen, including nitrousoxide. In: Delwiche J (ed) Denitrification, Nitrification and Nitrous Oxide. Wiley, New York, pp 17-44

Eghball B, Power JF, Gilley JE, Doran JW (1997) Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J Environ Qual 26 (1):189-193

Groot Koerkamp PWG, Metz JHM, Uenk GH, Phillips VR, Holden MR, Sneath RW, Short JL, White RP, Hartung J, Seedorf J, Schröder M, Linkert KH, Pedersen S, Takai H, Johnsen JO, Wathes CM (1998) Concentrations and emissions of ammonia in livestock buildings in Northern Europe. J Agric Eng Res 70:79-95

Hansen MN, Henriksen K, Sommer SG (2006) Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: Effects of covering. Atmos Environ 40 (22):4172-4181

Harper LA, Sharpe RR, Parkin TB (2000) Gaseous nitrogen emissions from anaerobic swine lagoons: Ammonia, nitrous oxide, and dinitrogen gas. J Environ Qual 29 (4):1356-1365

Hellebrand HJ, Kalk WD (2001) Emission of methane, nitrous oxide, and ammonia from dung windrows. Nutr Cycl Agroecosyst 60 (1-3):83-87

Houba VJG, Van Der Lee JJ, Novozamsky I, Walinga I (1989) Soil and plant analysis, a series of syllabi, Part 5. Wageningen University, the Netherlands

Hutchings NJ, Sommer SG, Andersen JM, Asman WAH (2001) A detailed ammonia emission inventory for Denmark. Atmos Environ 35 (11):1959-1968

Jeppsson KH (1999) Volatilization of ammonia in deep-litter systems with different bedding materials for young cattle. J Agric Eng Res 73 (1):49-57

Kirchmann H (1985) Losses, plant uptake and utilization of manure nitrogen during a production cycle. Acta Agri Scand Suppl 24:1-77

Kirchmann H, Witter E (1989) Ammonia volatilization during aerobic and anaerobic manure decomposition. Plant Soil 115 (1):35-41

Larney FJ, Buckley KE, Hao X, McCaughey WP (2006) Fresh, stockpiled, and composted beef cattle feedlot manure. J Environ Qual 35 (5):1844-1854

Levi-Minzi R, Riffaldi R, Saviozzi A (1986) Organic matter and nutrients in fresh and mature farmyard manure. Agr Wastes 16 (3):225-236

MAFF (1986) The analysis of agricultural materials. In: MAFF/ADAS Reference Book 427. 3rd edn. HMSO, London, United Kingdom,

Martins O, Dewes T (1992) Loss of nitrogenous compounds during composting of animal wastes. Bioresour Technol 42 (2):103-111

Misselbrook TH, Cape JN, Cardenas LM, Chadwick DR, Dragosits U, Hobbs PJ, Nemitz E, Reis S, Skiba U, Sutton MA (2011) Key unknowns in estimating atmospheric emissions from UK land management. Atmos Environ 45 (5):1067-1074

Moral R, Bustamante MA, Chadwick DR, Camp V, Misselbrook TH (2012) N and C transformations in stored cattle farmyard manure, including direct estimates of N_2 emission. Resour Conserv Recy 63:35-42

Mosquera J, Hol JMG, Monteny GJ (2006) Gaseous emissions from a deep litter farming system for dairy cattle. Int Congr Ser, vol 1293

Ndegwa PM, Hristov AN, Arogo J, Sheffield RE (2008) A review of ammonia emission mitigation techniques for concentrated animal feeding operations. Biosyst Eng 100 (4):453-469

Oenema O, Wrage N, Velthof GL, Van Groenigen JW, Dolfing J, Kuikman PJ (2005) Trends in global nitrous oxide emissions from animal production systems. Nutr Cycl Agroecosyst 72 (1):51-65

Parkinson R, Gibbs P, Burchett S, Misselbrook T (2004) Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. Bioresour Technol 91 (2):171-178

Petersen SO, Lind AM, Sommer SG (1998) Nitrogen and organic matter losses during storage of cattle and pig manure. J Agric Sci 130 (1):69-79

Pettygrove GS, Heinrich AL, Eagle AJ (2009) Dairy manure nutrient content and forms. Manure technical bulletin series

Predotova M, Schlecht E, Buerkert A (2010) Nitrogen and carbon losses from dung storage in urban gardens of Niamey, Niger. Nutr Cycl Agroecosyst 87 (1):103-114

Rashid MI, de Goede RGM, Brussaard L, Lantinga EA Home field advantage of cattle manure decomposition affects the apparent nitrogen recovery in production grassland. Soil Biol Biochem (0). doi:http://dx.doi.org/10.1016/j.soilbio.2012.10.005

Sagoo E, Williams JR, Chambers BJ, Boyles L (2005) Management techniques to minimise ammonia emissions from the storage and land spreading of pig FYM. In: the international workshop on green pork production, INRA, France pp 127-128

Sagoo E, Williams JR, Chambers BJ, Boyles LO, Matthews R, Chadwick DR (2007) Integrated management practices to minimise losses and maximise the crop nitrogen value of broiler litter. Biosyst Eng 97 (4):512-519

Shah GA, Shah GM, Groot JCJ, Groot Koerkamp PWG, Lantinga EA Bedding additives reduce nitrogen losses and improve fertilizer value of cattle straw manure. In review

Shah GM, Groot JCJ, Oenema O, Lantinga EA (2012a) Covered storage reduce losses and improve crop utilisation of nitrogen from solid cattle manure. Nutr Cycl Agroecosyst 94(2-3):299-313

Shah GM, Shah GA, Groot JCJ, Oenema O, Lantinga EA (2012b) Irrigation and lava meal use reduce ammonia emission and improve N utilization when solid cattle manure is applied to grassland. Agric Ecosyst Environ 160:59-65

Shah SB, Grabow GL, Westerman PW (2006) Ammonia adsorption in five types of flexible tubing materials. Appl Eng Agric 22 (6):919-923

Sommer SG, Dahl P (1999) Nutrient and carbon balance during the composting of deep litter. J Agric Eng Res 74 (2):145-153

Sommer SG, Møller HB (2000) Emission of greenhouse gases during composting of deep litter from pig production - Effect of straw content. J Agric Sci 134 (3):327-335

Sutton MA, Fowler D (2002) Introduction: Fluxes and impacts of atmospheric ammonia on national, landscape and farm scales. Environ Pollut 119 (1):7-8

Thomsen IK (2001) Recovery of nitrogen from composted and anaerobically stored manure labelled with 15N. Eur J Agron 15 (1):31-41

Thomsen IK, Olesen JE (2000) C and N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. J Agric Sci 135 (2):151-159

Webb J, Sommer SG, Kupper T, Groenestein K, Hutchings NJ, Eurich-Menden B, Rodhe L, Misselbrook TH, Amon B (2012) Emissions of ammonia, nitrous oxide and methane during the management of solid manures. Sustain Agri Rev 8:67-107

Yamulki S (2006) Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. Agric Ecosyst Environ 112 (2-3):140-14

Chapter 4

Covered storage reduces losses and improves crop utilisation of nitrogen from solid cattle manure

G.M. Shah, J.C.J. Groot, O. Oenema, E.A. Lantinga

Abstract

A 2-year study was carried out to examine the effects of solid cattle manure storage method on (i) total carbon (C) and nitrogen (N) losses, (ii) first-year and residual manure dry matter (DM) and N disappearance after litterbag placement on grassland, and (iii) apparent herbage N recovery (ANR) after a single surface application to a sandy grassland field. About twelve tonnes of fresh (FRE) manure taken from a litter barn were stored per treatment as stockpiled (STO), composted (COM) and covered (COV) heaps for 130 days, and total C and N losses were estimated. Thereafter, patterns of DM and N disappearance from FRE, COM and COV manures were monitored using litterbags with three mesh sizes (45 µm, 1 mm and 4 mm). Herbage ANR from these manures was measured at application rates of 200, 400 and 600 kg N ha^{-1}. During the storage period, only about 10% of the initial N_{total} was lost from the COV heap, whereas these losses were 31% from the STO heap and 46% from the COM heap. The respective C_{total} losses were 17, 59 and 67%. After field placement, overall manure DM and N disappearance rates from all mesh sizes of the litterbags were in the order: COV > FRE > COM ($P < 0.05$). Independent of N application rate, total herbage ANR was the highest from COV and the lowest from COM manure over two growing seasons (23 vs. 14%; $P < 0.05$). Including the N losses during storage, an almost three times higher herbage ANR (20 vs. 7%) of the manure N taken from the barn was observed by using COV vs. COM manure. In case of FRE manure this ANR fraction was 17%. It is concluded that COV storage reduced storage C and N losses to a minimum. After field application, manure stored under this method decomposed faster and more N was available for plant uptake, especially when compared to COM manure.

Keywords: Solid cattle manure, Manure storage, Surface application, Herbage N recovery, Grassland, Residual N effect, Litterbags

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4.1. Introduction

Application of animal manures to cropland is important for recycling of nutrient elements and for sequestration of carbon (C) in soil, but may cause agro-environmental problems when losses occur due to inefficient utilisation under poor management (Rotz 2004). In the manure management chain, the storage phase is critical since up to about 50% of the initial total nitrogen (N) and C can be lost during this step (Kirchmann 1985; Eghball et al. 1997; Larney et al. 2006). Attempts have been and are being made in developing effective techniques to reduce these losses. However, processes that determine the effectiveness of contrasting storage methods of manure in reducing N losses and increasing the final crop N availability after field application are not well understood yet. This understanding is essential for formulating efficient manure management plans.

Cattle are by far the largest producers of manure in the world, because of their large numbers and relatively large manure excretion rates (Sheldrick et al. 2003). The urine and faeces dropped by grazing cattle is left unmanaged in pastures, but the urine and faeces of cattle confined in barns is collected and managed. Depending on the chosen system, the liquid and solid fractions are collected separately or combined (as slurries). Solid cattle manure is a variable mixture of faeces plus bedding materials and absorbed urine. The urine of cattle consists mainly of urea N, which rapidly hydrolyses into ammonium N (NH_4^+-N) under the influence of the enzyme urease that is present in the faeces. Most of the N in faeces and bedding material (predominantly cereal straw) is bound in organic compounds and needs to be mineralised before it is available for plant uptake. However, the magnitude and quality of this fraction is dependent on the type of manure handling (Kirchmann 1985). The organic N fraction in solid cattle manure from the barn comprises 80-90% of the total manure N (Sommer and Hutchings 2001; Shah et al. 2012a). Generally, the N fertiliser value of cattle manures at field application depends on the mineral N content; it decreases in the order: liquid manure > slurry manure > solid manure.

After collection from barns, solid cattle manure is directly applied to the field and/or stockpiled or composted for an extended period of time prior to land application. Storing manure can cause a significant loss from the on-farm N cycle and will thus reduce the N fertiliser value of the manure to a certain extent, its size depending on the storage method (Rotz 2004). Sagoo et al. (2007) demonstrated that covering broiler litter with a plastic sheet can reduce total N losses during storage by 70% and ammonia (NH_3) emission by 90% compared to conventionally stockpiled manure heaps. Chadwick (2005) found that NH_3 emission during storage of solid cattle manure could be restricted by 50 to 90% through compaction and covering the heap with a plastic sheet. The storage conditions not only affect the level of N losses but also determine the composition of C and N containing compounds in the end product, which is decisive for subsequent nutrient release and crop N uptake. After covering a manure heap with an impermeable plastic sheet leading to anaerobic conditions, N can be contained in the form of NH_4^+-N (Kirchmann and Witter 1989; Thomsen and Olesen 2000), and during the fermentation process easily degradable organic compounds such as volatile fatty acids are produced (Kirchmann and Witter 1989). During composting, a considerable part of the manure NH_4^+-N will be lost via the process of NH_3 volatilisation especially under aerobic conditions just after turning, or transformed into organic N as humified organic material of high stability with a low C/N ratio (Kirchmann 1985). Consequently, after field application of composted manure, microbial decomposition and mineralisation activities in the soil are decreased with respect to anaerobically stored manure (Thomsen and Olesen 2000). For instance, Thomsen (2001) found a 16% higher plant N utilisation from the latter manure type during the year of application.

However, compared to slurry manures, only a relatively small fraction of the applied N with solid cattle manure becomes plant available during the year of application because of the slow-release characteristics of the organically bound manure N (Schröder et al. 2007). Moreover, part of the applied N is subject to microbial immobilisation (Gutser et al. 2005). Nevertheless, these organic N fractions will become plant-available to a certain extent due to mineralisation in the following years (Gutser et al. 2005; Muñoz et al. 2008). However, to our knowledge no comparative trial has been done so far to estimate N recovery during the first-year as well as the year thereafter from solid cattle manure subjected to different storage conditions including covered storage.

The aims of this study were to (i) evaluate the effects of three contrasting storage methods of solid cattle manure on total C and N losses, and (ii) examine and compare first-year and residual dry matter (DM) and N degradability together with herbage N recovery following application of fresh, composted and covered solid cattle manures to grassland.

4.2. Materials and methods

4.2.1. Manure storage

Solid beef cattle manure (not older than 1 week) was taken from a sloping floor litter-barn, where cereal straw was used as bedding material at a daily rate of 5 kg per livestock unit. Immediately thereafter, approximately 12.5 Mg manure per treatment was put on a clean concrete floor to make three conical heaps with a height of about 1.5 m and a base diameter of about 4 m. The manure was stored as: (i) stockpiled (STO) heap, (ii) composted (COM) heap, with infrequent turning, and (iii) covered (COV) heap under a plastic sheet. The first two heaps were made in a roofed building to prevent leaching losses during rainfall. The COM heap was turned once every month using a tractor with a front end-loader. For the COV heap, a plastic sheet (0.15 mm thick polyethylene film) was placed at the bottom and over the heap to make it completely airtight. Temperatures in the centre of each heap were monitored throughout the whole storage period using a hand-held probe. The manure was stored for 130 days starting from mid-January until the end of May 2009.

4.2.2. Field experiments

After the storage phase, COM and COV manures together with fresh (FRE) manure taken directly from the barn were applied in two experiments on a sandy grassland field at the Organic Experimental and Training Farm Droevendaal, ca. 1 km north of Wageningen, the Netherlands (latitude 55°99'N and longitude 5°66'E). It was observed that C and N losses from the STO heap were in between those from the COM and COV heaps and therefore, in order to achieve the greatest contrast, we decided to replace STO manure with FRE manure taken directly from the barn. Due to logistic reasons, it was not possible to include all the treatments in the field experiments. Expt. 1 was a litterbag study aimed to estimate magnitude and patterns of total manure DM and N disappearance over two consecutive years. Expt. 2 was designed to estimate first-year and residual herbage N recovery after a single manure application. Both experiments were conducted in parallel and within the same field. Chemical analysis of soil (0-30 cm layer) sampled from the experimental field in March 2009 showed that it contained: OM 51 g kg^{-1}, total N 2 g kg^{-1}, nitrate-N (NO_3^--N) 1.5 mg kg^{-1}, NH_4^+-N 0.5 mg kg^{-1}, C/N ratio 15, and pH-KCl 5.3. All these analyses were done according to methods described later. The field had been in rye, spring barley and yellow mustard for the preceding two years before sowing with perennial ryegrass

(*Lolium perenne* L.) in September 2008 (seeding rate 35 kg ha^{-1}) and had not been part of any experiment during the previous years. The pre-experimental treatment consisted of regular cutting of the herbage to a stubble height of 4 cm with the last harvest one month before manure application.

4.2.2.1. ***Litterbag experiments*** *(Expts. 1a and b)*

On the final day of manure storage, litterbags (10 cm × 10 cm) were filled with 70 g (fresh wt. basis) of FRE, COM and COV manures. These were made of nylon with three mesh sizes (45 µm, 1 mm and 4 mm) in order to estimate the role of different types of soil organisms on manure DM and N disappearances (Expt. 1a). The largest mesh size of 4 mm was used to allow the entrance of 'all' soil fauna to the material inside the litterbag, the 1 mm mesh excluded only macrofauna, whereas the 45 µm mesh allowed only colonisation by microorganisms (Bradford et al. 2002; Rutgers et al. 2008, 2009). These mesh sizes were selected keeping in view the results from previous studies on Dutch sandy grasslands, which classified the existing soil organisms in the region according to their body width (e.g. Rutgers et al. 2008, 2009).

After filling, litterbags were randomly placed horizontally on the soil surface of the grassland in three replicate blocks during the last week of May 2009. Just before their placement, the vegetated soil surface in the 10 cm × 10 cm area was gently roughened with a spade to facilitate optimal soil-litterbag contact. The distance between two consecutive litterbags was kept at 30 cm. From each replicate, one litterbag of each mesh size and manure type was removed after 15, 33, 63, 123, 168, 395, 457 and 528 days of incubation for analysis. At each sampling, the leftover manure in litterbags was oven-dried at 105°C for 24 hours, weighed, ground to pass a 1 mm sieve and analysed for total N and ash content according to the procedures described below. The level of soil contamination in the litterbags was determined according to Cusick et al. (2006) as

$$\mathrm{S_C} = \frac{\mathrm{AR_{LB}} - \mathrm{AR_M}}{\mathrm{AR_S}} \qquad (4.1)$$

Where S_c is the dry weight of soil contamination (g), AR_{LB} is the ash residue of the total material in the litterbags (mg), AR_M is the initial ash residue of the manure (mg) and AR_S is the ash residue of the soil (mg g^{-1}).

Manure DM and N disappearances at each sampling event were expressed relative to their initial amounts. Thereafter, patterns of manure DM and N disappearance during the year of manure application were fitted using the mono-component model as described by Yang and Janssen (2000). This fitting procedure could not be extended to the second year due to the winter break.

In a separate parallel sub-experiment in the same field (Expt. 1b), litterbags (10 cm × 10 cm) of the same three mesh sizes (45 µm, 1 mm and 4 mm) and filled with the same three manure types (FRE, COM and COV) were randomly placed on the soil surface in the middle of plots each measuring 40 cm × 40 cm. Also here the vegetated soil surface below the litterbags was gently roughened. The control consisted of a non-decomposable piece of wood with the same size as of the litterbags. The treatments were arranged in a randomised complete block design with four replicates. The purpose of this experiment was to record the time pattern of apparent herbage N recovery from manure released N. Therefore, herbage growing up to 15 cm around the litterbags and the controls was cut to a stubble height of 1 cm with a spinach knife after 47, 96, 168, 395, 457 and 528 days of incubation.

*4.2.2.2. **Manure-application experiment** (Expt. 2)*

FRE, COM and COV manures (rates: 200, 400 and 600 kg N ha^{-1}) were surface-applied to grassland at once during the last week of May 2009. This was done manually using pitchforks in experimental units each measuring 6 m × 3 m. All treatments, including a non-fertilised control, were arranged in a randomised complete block design with four replicates. During the first-year, the grass sward was harvested four times (9 July, 26 August, 29 September and 9 November 2009) and three times in the year thereafter (15 June, 22 August and 8 November 2010). At each harvest, herbage was cut to a height of 4 cm above the soil surface using a motor mower with a cutting bar width of 0.9 m. The net area cut for analysis from each plot was the inner 5.4 m^2 (6 m × 0.9 m) to avoid border effects.

4.2.3. Sampling, analysis and calculations

*4.2.3.1. **Manure***

At the start and at end of the storage period, three composite manure samples (ca. 2 kg fresh wt. per sample) were collected from each heap. Each composite sample consisted of 20-30 sub-samples taken by hand from different locations of a heap. The samples were stored at -18°C for future analyses. Before analysis, the samples were thawed at room temperature (20°C) and subsequently chopped with a cutting machine in order to cut the straw particles into small pieces (Sommer and Dahl 1999). From this material, representative sub-samples of about 100 g were analysed for total N, NH_4^+-N, NO_3^--N, pH, DM and raw ash (Table 4.1). Total N in the manure was measured after Kjeldahl digestion (MAFF 1986). Contents of NH_4^+-N and NO_3^--N were measured in a 1:10 manure/0.01 M $CaCl_2$ extract by means of segmented-flow analysis (Houba et al. 1989). The pH was measured in the same extract using a pH meter. The DM content was determined after drying the samples at 105°C for 24 hours. Subsequently, raw ash content was determined gravimetrically following ignition of the dried samples at 525°C for 6 hours (Anonymous 1998) with the organic matter (OM) content being equal to the ignition loss. Total manure C was assumed to be 50% of the OM (Pettygrove et al. 2009). The mass of raw ash in the heaps was conserved because of the absence of leaching and erosion, and changes in ash content could thus serve as a basis for estimating DM and nutrient losses during the storage period (Dewes 1995; Petersen et al. 1998; Larney et al. 2006). Total DM, C and N losses during the storage period were estimated by comparing their contents relative to the raw ash fraction at the start and at end. Just before application, contents of cellulose, hemi-cellulose and lignin in the manures (Table 4.2) were determined gravimetrically after extracting the dried samples with sulphuric acid as outlined in Dence (1992) (the NDF/ADF method).

4.2.3.2. Herbage

Fresh herbage yield was measured in the field and representative samples were oven-dried at 70°C for 48 hours (Sharkey 1970). Thereafter, dried material was weighed, ground to pass a 1 mm sieve and analysed for total N following Kjeldahl digestion (MAFF 1986). Subsequently, N uptake from each harvest was cumulated to estimate total apparent N recovery from the field-applied manure (ANR_F) as

$$\mathrm{ANR_F}\ (\%) = \frac{\mathrm{TNU_{manure}} - \mathrm{TNU_{control}}}{\mathrm{TN_{applied}}} \times 100 \qquad (4.2)$$

Where TNU_{manure} is total herbage N uptake from manure treated plots (kg ha^{-1}), $TNU_{control}$ is total herbage N uptake from control plots (kg ha^{-1}) and $TN_{applied}$ is total manure N applied (kg ha^{-1}).

For the manure-application experiment, ANR as a fraction of the manure N collected from the barn (ANR_B) was calculated by considering the N loss

Table 4.1. Chemical characteristics (means±standard errors, n = 3) of solid cattle manures before and after storage.

	DM	Raw ash	C_{total}	N_{total}	$N_{mineral}$	$N_{organic}$	N_{min}/N_{tot}	C/N	pH‡
	($g\ kg^{-1}$)	($g\ kg^{-1}$ DM)					(%)		
Before storage									
Fresh manure	187±2	176±12	412±6	28.8±0.2	6.4±0.8	22.4±0.6	22	14	7.4
After storage									
(i) Stockpiled	208±3	340±2	330±2	38.2±0.1	1.0 ±0.1	37.5±0.1	3	9	7.7
(ii) Composted	215±3	390±6	304±3	34.3±0.2	5.1 ±0.5	29.3±0.7	15	9	8.1
(iii) Covered	180±2	205±3	397±2	30.1±0.4	9.5 ±0.8	20.6±0.5	32	13	7.0

‡ Standard error < 0.1

Table 4.2. Chemical composition (means±standard errors; n = 3) of fresh (FRE), composted (COM) and covered (COV) manures at the time of application

Manure	DM	Total N	NH_4-N	$N_{organic}$	Hemi-cellulose	Lignin	Cellulose	Lignin/N	C/N
	($g\ kg^{-1}$)	($g\ kg^{-1}$ DM)			(% DM)				
FRE	187±3	27.8±0.4	3.7±0.4	24.1±0.8	17±1.2	22±1.3	26±0.1	7.9	14
COM	215±3	34.3±0.2	5.1±0.5	29.3±0.7	01±0.4	36±0.5	12±0.2	10.5	9
COV	180±2	30.1±0.4	9.5±0.8	20.6±0.5	21±1.2	21±1.9	24±1.3	6.9	13

fraction during the storage phase as

$$\mathrm{ANR_B}\ (\%) = \frac{(\mathrm{TN_{barn}} - \mathrm{TNloss_{storage}}) \times \mathrm{ANR_F}}{\mathrm{TN_{barn}}} \times 100 \qquad (4.3)$$

Where TN_{barn} is total amount of the manure N taken from the barn (kg), $TNloss_{storage}$ is total N lost during storage (kg) and ANR_F is apparent herbage N recovery in the field (%) calculated from equation 4.2.

4.2.3.3. Soil

During May 2009 and August 2010, soil samples from the experimental area of the field were taken to analyse a number of biological parameters. The purpose was to estimate the density of micro-, meso- and macrofauna on an area basis (m^2) and correlate it with manure DM and N disappearance from the various mesh sizes of the litterbags. In 2009, the soil sampling was done just before manure application and only earthworm densities were determined, whereas in 2010 it was done from the manured plots and in total four groups of biological parameters were measured, as outlined below.

Earthworms: Ten random soil blocks each of 20 cm × 20 cm 20 cm size were sampled from the experimental area of the field. Each time after excavating the soil block, earthworms were hand-sorted in the field and transferred to plastic bottles containing some soil. Afterwards, the bottles were shifted to the laboratory where earthworms were rinsed with tap water, counted, cleaned, weighed and placed in an oven at 15°C for 48 hours in order to empty their guts. Thereafter, they were weighed and fixed with 70% ethanol prior to identification. Earthworms were first divided into juveniles and adults, and further distinguished into epigeic, endogeic and anecic species.

Enchytraeids: Three random soil samples from the field were taken using a separable core sampler of 15 cm length and 5.8 cm diameter. The sampler contained six polyvinyl chloride (PVC) rings each of 2.5 cm height since the vertical distribution of enchytraeids can be up to 15 cm of the soil profile (Persson et al. 1980). After sampling, enchytraeids from the soil in rings were extracted with the modified wet extraction method (Didden and Römbke 2001). Thereafter, the organisms were counted using a light microscope.

Micro-arthropods: Three random soil samples were collected using a separable core sampler (7.5 cm length and 5.8 cm diameter) holding three PVC rings each of 2.5 cm height. A lower sampling depth was selected for micro-arthropods than enchytraeids because existence of the formers is restricted to the top 7 cm of the soil profile (Persson et al. 1980). After sampling, the rings were placed in a Tullgren funnel for 7 days in order to extract micro-arthropods from the soil (Römbke et al. 2006). In the upper part of the funnel the temperature was set at 30°C, whereas it was kept at 5°C in the lower parts. To escape from heat, organisms moved downwards, dropped through the funnel and were collected in a plastic bottle containing 70% ethanol. Afterwards, springtails and mites were counted separately using a light microscope.

Microbial parameters: Analyses of the microbial community were performed by taking 3 representative samples from the field. Each sample was a composite of 60 sub-samples taken with an auger from various locations of the field. From each of the representative samples, a sub-sample of 200 g was adjusted to 50% water holding capacity and pre-incubated at 12°C for four weeks to stabilise the soil conditions and to avoid temperature and moisture fluctuations which are apparent in the field (Bloem et al. 2006; Van Eekeren 2008). Thereafter, fungal and bacterial biomasses as well as their activities were measured according to the procedures described by Van Eekeren (2008).

4.2.4. Statistical analysis

The litterbag experiments (Expts. 1a and b) were designed as a 2-factor mixed model. The factors/treatments were manure and litterbag types. In addition, the interactions between these factors/treatments were tested. The overall significance of treatment effects and their interaction with manure DM and N disappearance during each year were assessed using analysis of variance (ANOVA) in Genstat (13^{th} Edition, VSN International, Hemel Hempstead, UK). If the overall main effects were significant, differences among the treatments were further compared using Fisher's protected least significant difference (LSD) test at 5% probability level.

First-year and residual herbage N uptake as well as N recovery in Expt. 2 were statistically analysed in the same way as described above. However, treatments in this case were manure type and N application rate. The significance of the main effects and their interactions were assessed using ANOVA in Genstat. Thereafter, significant differences among the treatments were distinguished by Fisher's protected LSD test at 5% probability level.

Patterns of manure DM and N disappearance from the litterbags were fitted using the mono-component mineralisation model as described by Yang and Janssen (2000). The disappearance rate, K, was calculated by means of

$$K = Rt^{-S} \qquad (4.4)$$

Where R (dimension t^{S-1}) represents K at t = 1, and S (dimensionless, $1 \geq S \geq 0$) is a measure of the rate at which K decreases over time. Thereafter, the amount of remaining DM and N at time t (Y_t) was calculated as

$$Y_t = Y_0 \exp(-Rt^{1-S}) \qquad (4.5)$$

Where, Y_o is the initial amount of DM or N in the litterbags. The model parameters R and S were optimised for this non-linear regression equation using PASW statistics 17 (data not presented).

4.3. Results

4.3.1. Total C and N losses from manure during storage

Visual observations revealed that all the heaps had decreased in size noticeably after the storage period. About 22% of the initial DM was lost from the COV heap, whereas this fraction exceeded more than 50% in case of the STO and COM heaps (Fig. 4.1). Also the C and N losses were lowest for the COV heap (Fig. 4.1).

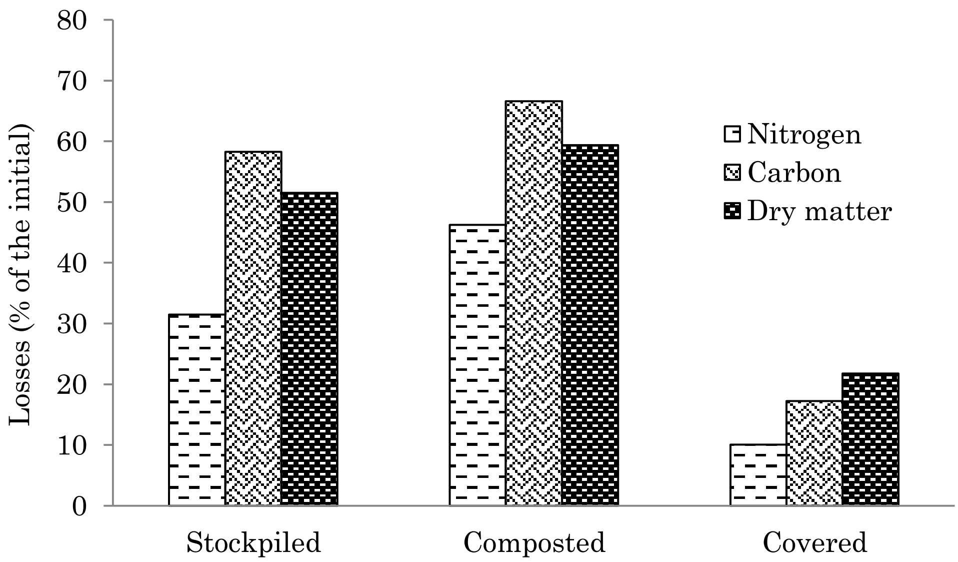

Fig. 4.1. Total dry matter, carbon and nitrogen losses from solid cattle manure subjected to different storage methods during a period of 130 days. Error bars represent standard error (±) of the mean.

In the STO and COM heaps, temperatures increased up to 60°C within a month after their establishment, declined thereafter and stabilised around 20°C at the end of the storage period (data not shown). In the COV heap, the highest temperature of about 25°C was observed within a few days after its establishment. Subsequently, it declined gradually and stabilised around 17°C (data not shown).

At the end of the storage period, inorganic N content had increased in COV manure, whereas it had decreased considerably in STO and COM manures (Table 4.1). A decrease in pH was observed in COV manure, whereas it increased in case of STO and COM manures. In the latter two manure types, total C/N ratio was decreased due to greater C than N losses during the storage phase (Table 4.1).

4.3.2. DM and N disappearances from manure in litterbags (Expts. 1a and b)

Fractions of total manure DM and N that had disappeared from the litterbags during the first and over two years are presented in Table 4.3 and 4.4, respectively. For each manure and litterbag combination, disappearance rates of both DM and N were highest till day 15 and declined gradually thereafter (Figs. 4.2a and b). Among the litterbag mesh sizes, at each sampling date considerably

Table 4.3. Mean (n = 3) manure dry matter (DM) and nitrogen (N) disappearance from fresh (FRE), composted (COM) and covered (COV) manures in litterbags after 168 days (in 2009) of placement.

	DM disappearance (%)				N disappearance (%)			
	FRE	COM	COV	P-value†	FRE	COM	COV	P-value†
L1¡	$30^{a\ddagger}$	22^{a}	42^{a}	<0.001	35^{a}	33^{a}	46^{a}	0.002
L2‼	34^{a}	25^{a}	46^{b}	<0.001	43^{b}	41^{b}	60^{b}	<0.001
L3ǀ	40^{b}	30^{b}	48^{b}	<0.001	51^{c}	44^{b}	69^{c}	<0.001

† Probability values of the comparison among manure types filled in litterbags with the same mesh size.

¡ Litterbags of 45 µm mesh size for the entrance of only microfauna.

‼ Litterbags of 1 mm mesh size for micro- and mesofauna.

ǀ Litterbags of 4 mm mesh size for all soil fauna.

‡ Values within a column having different letters as superscript are significantly different from each other.

Table 4.4. Mean (n = 3) manure dry matter (DM) and nitrogen (N) disappearance from fresh (FRE), composted (COM) and covered (COV) manures in litterbags after 528 days (2009-2010) of placement.

	DM disappearance (%)				N disappearance (%)			
	FRE	COM	COV	P-value[†]	FRE	COM	COV	P-value[†]
L1[¡]	51^{a‡}	26^{a}	63^{a}	<0.001	50^{a}	40^{a}	63^{a}	0.022
L2[‼]	52^{a}	28^{a}	66^{a}	<0.001	60^{a}	45^{a}	70^{a}	0.010
L3[ǀ]	82^{b}	55^{b}	87^{b}	0.003	83^{b}	70^{b}	85^{b}	0.042

† Probability values of the comparisons among manure types filled in litterbags of the same mesh size.

¡ Litterbags of 45 µm mesh size for the entrance of only microfauna.

‼ Litterbags of 1 mm mesh size for micro- and mesofauna.

ǀ Litterbags of 4 mm mesh size for all soil fauna.

‡ Values within a column having different letters as superscript are significantly different from each other.

higher DM and N disappearances were observed in the 4 mm litterbags, irrespective of manure type. During the first 15 days, about 11% of the initial manure DM from FRE, 4% from COM and 24% from COV manure had disappeared, whereas the respective values for N were 36, 29 and 53% ($P < 0.05$). Both for the 1 mm as well as the 45 µm mesh litterbags, similar trends were observed (COV > FRE > COM), but there were no significant differences between these two mesh sizes (data not shown). After 15 days, manure disappearance rates declined in each litterbag type and at the end of the first season (168 days) the amounts of disappeared DM and N were still in the order: COV > FRE ≥ COM (Table 4.3; $P < 0.01$).

In the second year, patterns of DM and N disappearance continued for all manure types and litterbag mesh sizes. At the end of the experiment, both of these parameters were lowest for COM manure (Table 4.4; $P < 0.05$), but there was no difference between the litterbags of the two smallest mesh sizes (Table 4.4; $P > 0.05$). At the end of the 528-days experimental period, about 70, 83 and 85% of the initial N in 4 mm mesh litterbags had disappeared from COM, FRE and COV manures, respectively (Table 4.4). Of this total disappeared N, about 80% was recovered in aboveground herbage (Fig. 4.3). Over the whole experimental period, 63% of the initial N in the litterbags was recovered in the aboveground herbage from FRE, 53% from COM and 76% from COV manure filled in 4 mm

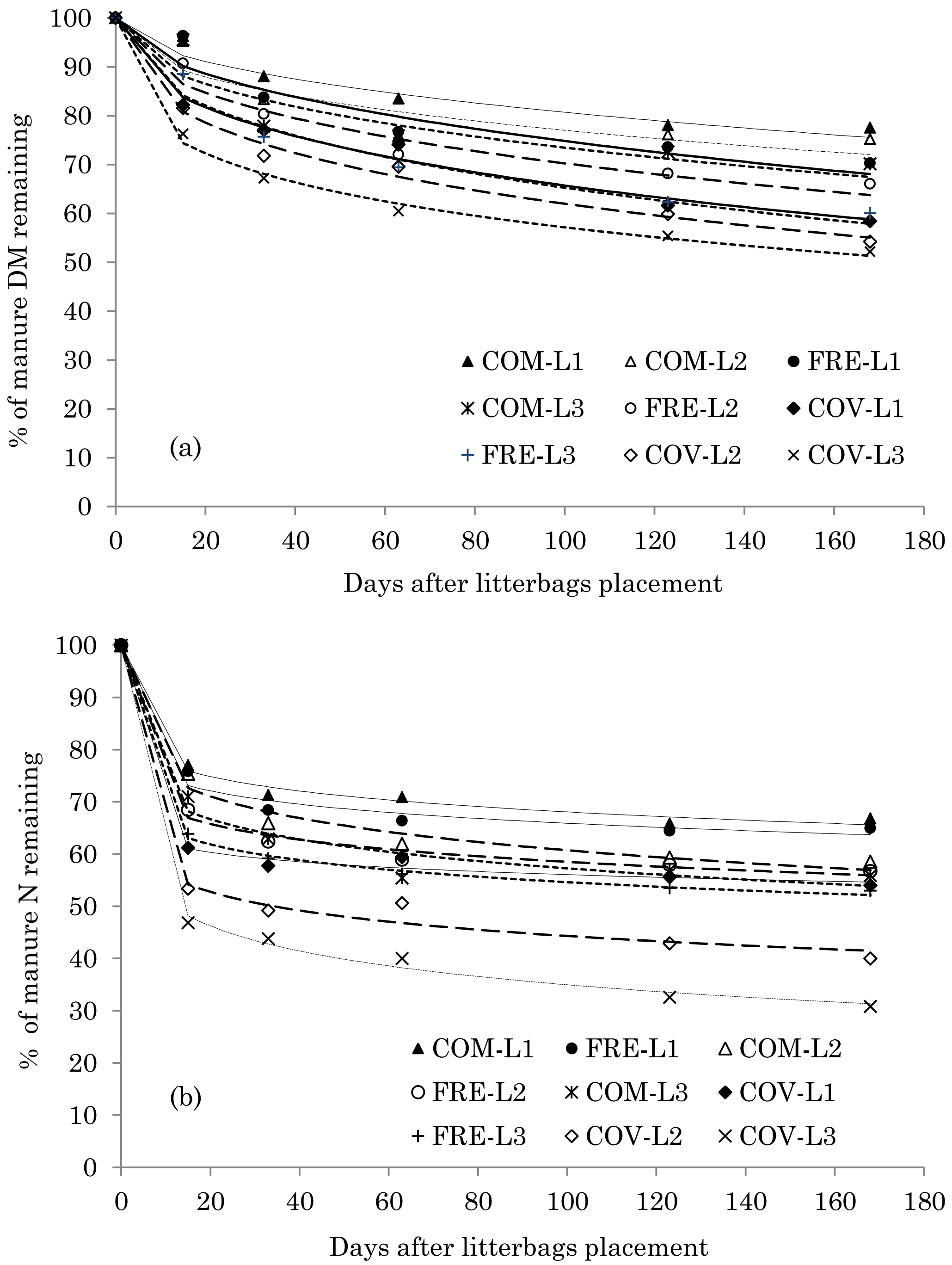

Fig. 4.2. (Expt. 1a) Remaining fractions of (a) total dry matter (DM) and (b) total nitrogen (N) from fresh (FRE), composted (COM) and covered (COV) solid cattle manures in litterbags with mesh sizes of 45 μm (L1), 1 mm (L2) and 4 mm (L3). Symbols represent the means. Lines are fitted with equation Yt = Y0*exp (-R*t^ (1-S)). The solid, dashed and dotted lines represent the litterbags of 45 μm, 1 mm and 4 mm mesh size, respectively.

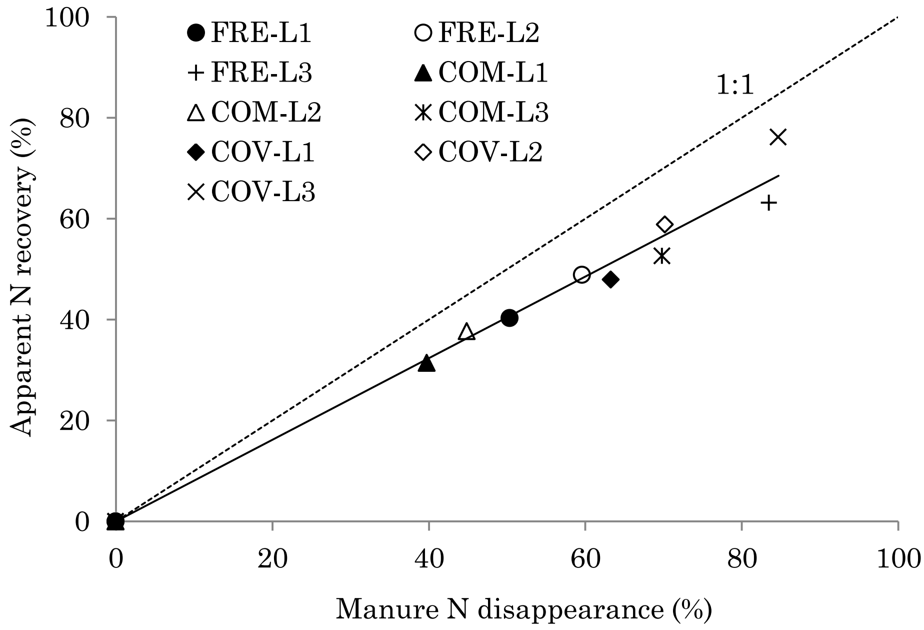

Fig. 4.3. (Expts. 1a and b) Relationship between nitrogen (N) disappearance and apparent herbage N recovery from fresh (FRE), composted (COM) and covered (COV) solid cattle manures filled in litterbags of three mesh sizes (L1 = 45 µm mesh, L2 = 1 mm mesh and L3 = 4 mm mesh). The dotted line represents the 1:1 relationship; the straight line is the linear fit through the origin ($y = 0.81x$, $R^2 = 0.97$).

mesh litterbags (Fig. 4.3). From the other two litterbag types, relatively lower herbage ANR_F was observed from all of the manures, which corresponded well with the lower amount of N disappeared from these litterbags. Of the total herbage recovery of the released N from all treatments, the highest contribution came from the first grass harvest, and the amount of recovered N gradually decreased in the subsequent harvests (data not shown), coinciding with their N release pattern from the litterbags.

From the differences in DM and N disappearance from litterbags with different mesh sizes, it was derived that the contribution of the microfauna to the total DM disappearance was between 73 and 88% during the first year, whereas in case of N disappearance the respective fractions were between 67 and 75% (Table 4.3). Over both years between 47 and 72% of the total DM disappearance and between 57 and 74% of the total N disappearance could be attributed to microbial activities (Table 4.4). Contribution of macrofauna was between 4 to 17% for total DM disappearance and 7 to 16% for total N disappearance during the first year (Table 4.3). Over the two years, the contribution of the macrofauna was up to 49% for total DM and up to 36% for total N disappearance indicating their pronounced role in the second year. Throughout the whole experiment, mesofauna played a minor role.

4.3.3. First-year and residual manure N recovery (Expt. 2)

The observed cumulative herbage N uptake and DM yield over two growing seasons from the field-applied manures are presented in Fig. 4.4. For each manure type, N uptake responded linearly to increasing rates of N application. At a given level of N application, herbage ANR_F during the year of manure application as well as the residual year was in the order: COV > FRE > COM (Table 4.5; $P < 0.05$). Over the two growing seasons, about 23% of the total N applied with COV, 17% with FRE and 14% with COM manure was recovered in the aboveground herbage cut at a stubble height of 4 cm (Table 4.5). Of this ANR_F fraction, only up to about 5% was realised during the second experimental year. Taking also into account the N losses during storage, a three times higher recovery of the N taken from the barn could be calculated for COV compared to COM manure. However, the storage methods themselves did not have an influence on the herbage N use efficiency (kg DM production (kg N uptake)$^{-1}$), since treatment differences in DM yield were absent at a given level of cumulative N uptake (Fig. 4.4).

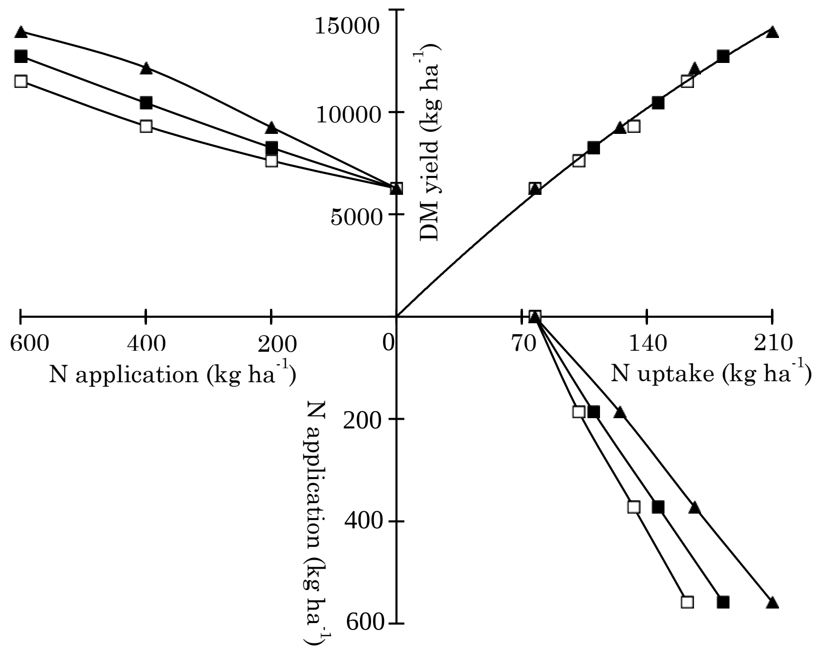

Fig. 4.4. (Expt. 2) Relationship between nitrogen (N) application, total herbage N uptake and total herbage dry matter (DM) yield after two growing seasons. Manure types: fresh (closed squares), composted (open squares) and covered (closed triangles).

Table 4.5. Mean (n = 4) first and second year apparent herbage N recovery from fresh (FRE), composted (COM) and covered (COV) manures expressed as fraction of the total amount of N applied to the field (ANR_F) or taken from the barn (ANR_B).

Manure	N application (kg ha^{-1})	ANR_F (%) Year 1	Year 2	Total	ANR_B (%)
FRE	200	13.2	3.2	16.4	16.4
	400	13.8	3.3	17.1	17.1
	600	14.1	3.3	17.4	17.4
	mean	13.7	3.3	17.0	17.0
COM	200	10.3	1.9	12.2	6.6
	400	11.9	1.9	13.8	7.5
	600	12.5	2.7	15.2	8.2
	mean	11.6	2.2	13.8	7.4
COV	200	18.6	5.1	23.7	21.3
	400	17.3	5.0	22.3	20.1
	600	17.6	4.4	22.0	19.8
	mean	17.8	4.8	22.6	20.4
Statistical analysis (P values)					
Manure type (M)		<0.001	<0.001	<0.001	<0.001
Application rate (R)		0.752	0.985	0.816	0.913
M*R		0.707	0.817	0.706	0.765

4.4. Discussion

4.4.1. Total C and N losses from manure during storage

Storage methods had diverging effects on manure DM, C and N losses. All these losses were much higher from the STO and COM heaps compared to the COV heap (Fig. 4.1). This can be associated with a higher degree of aerobic decomposition stimulated by diffusion of air into these heaps due to (i) the presence of straw in both heaps and (ii) regular turning of the COM heap (Parkinson et al. 2004). This was reflected in the measured temperatures which reached up to 60°C in the STO and COM heaps and did not exceed 25°C under the plastic cover of the COV heap. Covering blocks air circulation inhibits OM degradation and lowers internal heat production, which ultimately decreases C and N losses (Kirchmann 1985; Hansen et al. 2006).

4.4.2. Manure N disappearance and recovery after field application

After field application, the disappearance of DM and N from each type of litterbags was lower for COM than COV or FRE manure. The reasons for this are twofold: (i) loss of readily degradable C and N compounds already during composting and (ii) conversion of part of the remaining C and N into chemical forms that are more stable than those originally present before composting (Kirchmann 1985; Levi-Minzi et al. 1986: Kirchmann and Witter 1989; Thomsen 2001). It is known that a large part of the organic N formed during composting consists of amino-sugars, which act as antimicrobial compounds (Bremner 1965), whereas water-soluble and easily hydrolysable sugars are being reduced (Sana and Soliva 1987). Jenkinson and Tinsley (1959) have found associations between the N compounds and lignin fractions as lignoproteins in extracts of compost. This chemical association protects the degradation of proteins (Bremner 1965). This explains the relatively lower N disappearance from our COM manure after field application since its lignin content as well as the lignin-to-N ratio was highest (Table 4.2). In contrast, easily degradable low molecular compounds such as volatile fatty acids, alcohols and phenols together with NH_4^+-N are formed under COV storage (Kirchmann 1985; Kirchmann and Witter 1989). The larger stability of N compounds in COM manure resulted in a 40% lower ANR_F over two growing seasons compared to COV manure (23 vs. 14%; Table 4.5).

When losses during storage were included in the recovery calculations to arrive at the apparent N recovery for the whole chain starting from the barn (ANR_B), a considerably lower value was observed for COM with respect to COV and FRE manures (7 vs. 20 and 17%). Interestingly, despite the 10% N loss during COV storage, ANR_F from COV manure was 18% higher compared to that from FRE manure. This indicates that with this storage method more N will become available for crop uptake. However, due to the higher amount of mineral N in the manure left after COV storage compared to the COM method, compensatory losses can occur through increased NH_3 emission after field application. Nevertheless, it still provides a tempting managerial chance to further improve solid cattle manure N utilisation, which is absent when easily decomposable N is already lost during the storage phase. Hence, additional management measures are to be recommended, such as the use of lava meal as a manure additive and/or irrigation after surface application. These options have been shown to be effective in reducing losses and improving utilisation of N from COV manure (Shah et al. 2012b). Application of COV manure just before a predicted moderate rainfall event would provide the cheapest option to improve the agro-environmental value of solid cattle manure. Rainfall immediately after manure spreading lowers the manure surface temperature, dilutes total ammoniacal N (TAN) concentration, and enhances TAN infiltration into (i) the inner side of the manure clumps where it might be safeguarded from exposure to the external temperature and wind, and (ii) the soil where it can be protected against volatilization by sorption onto the soil colloids (Sommer and Hutchings 2001; Misselbrook et al. 2005; Mkhabela et al. 2009).

4.4.3. Effect of soil organisms on DM and N disappearances

Manure DM and N disappearances increased sharply during the first 15 days from all the manure and litterbag types. Hereafter, the disappearance rates declined (Figs. 4.2a and b) because of depletion of readily degradable C and N compounds.

Overall, the role of microorganisms in DM and N disappearances was well pronounced, especially in the year of manure application. Their role was limited during the second year because of the greater stability of the leftover C and N compounds in the litterbags. The lowest disappearance values in the field were observed for COM manure which is known to be rich in stable C and N compounds (Kirchmann 1985). The primary decomposition pathway was fungal dominant since the biomass and activity of bacteria in our experimental field was about ten times lower than the average values of Dutch sandy grasslands (Table 4.6). The population density of the mesofauna, especially the micro-arthropods, in our field was about four times lower compared to the Dutch average (Table 4.6), which was in line with the lack of significant differences in DM and N disappearances between the 1 mm and 45 µm mesh litterbags (Table 4.4).

As expected, the highest disappearance of both DM and N was observed from 4 mm mesh litterbags due to the additional activities of macrofauna. Visual observations within or below the 4 mm mesh litterbags revealed the presence of earthworms, dung beetles, millipedes, ants, snail and slugs. Soil macrofauna, especially earthworms, comminute organic materials, facilitate movement of the fragmented material down the soil profile and transform the material into more digestible forms for microorganisms thereby stimulating nutrient release (Bradford et al. 2002; Aira et al. 2008). Density of earthworms in our experimental field at the start was only 108 m^{-2} out of which 85% were juvenile (Table 4.6), thus restricting the disappearance of DM and N from 4 mm mesh litterbags in the beginning. However, it increased from 108 to 513 m^{-2} within seventeen months after manure application and was about three times higher compared to the average value of Dutch sandy grasslands (Table 4.6).

Table 4.6. Soil biota characteristics in the experimental field and average values of Dutch sandy grasslands (Rutgers et al. 2008). Values in parentheses represent standard errors of the mean.

Soil biological parameters	Experimental field		Dutch sandy
	May 2009	October 2010	grasslands
(1) Earthworms (n‡ = 10)			
- Total (no. m^{-2})	108 (±30)	513 (±73)	163
- Adults (no. m^{-2})	17 (±8)	118 (±30)	na
- Juvenile (no. m^{-2})	92 (±22)	395 (±45)	na
- Epigeic (no. m^{-2})	-[a]	298 (±41)	na
- Endogeic	-	215 (±34)	na
- Average wt./worms (g)	-	0.19 (±0.02)	na
(2) Enchytraeids (n = 3)			
- Total (no. m^{-2})	-	44643 (±16728)	24800
(3) Microarthropodes (n = 3)			
- Total (no. m^{-2})	-	11135 (±2449)	44700
- Springtails (no. m^{-2})	-	6047 (±1698)	na
- Mites (no. m^{-2})	-	5088 (±1101)	na
(4) Microbial parameters (n = 3)			
- Fungi biomass (µg C g^{-1} dry soil)	-	21 (±4)	22
- Active fungi (%)	-	30 (±3)	na
- Bacteria biomass (µg C g^{-1} dry soil)	-	11 (±1)	146
- Bacterial activity Thymidine (pmol g^{-1} h^{-1})	-	5 (±1)	65
- Bacterial activity Leucine (pmol g^{-1} h^{-1})	-	252 (±53)	na

[a] Not determined; na; not available.

‡ Number of samples at each sampling event.

Consequently, in the second year the differences in DM and N disappearance between 4 mm vs. 1 mm or 45 µm mesh litterbags were more pronounced, irrespective of manure type (Table 4.6).

4.4.4. Apparent N recovery from applied manure

The recovery of N in aboveground herbage around the litterbags was linearly related to N disappearance from litterbags, with the lowest value for COM and the highest for COV manure (Fig. 4.3). Total mean herbage ANR_F was considerably lower in the manure-application than in the litterbag experiment (~20 vs. ~76%). This can be attributed to the following four reasons. Firstly, the field-applied manure was more exposed to sunlight and wind, which results in larger N losses through NH_3 volatilisation. According to Huijsmans et al. (2007), NH_3 emission from surface-applied solid cattle manure to grassland can be up to 100% of the total ammoniacal N content. Secondly, the stubble of the newly-sown grass sward was still not completely established at the start of the manure-application experiment. Therefore, during the first months the grass plants were still accumulating part of the absorbed N in the stubble layer until the equilibrium tiller density under the imposed harvesting regime was achieved. This fraction was not harvested since the grass was cut at a stubble height of 4 cm with the motor mower. In case of the litterbag experiment, the herbage harvesting height was close to ground level, which greatly increased the harvested proportion of the accumulated N aboveground. Thirdly, the N application rates were much lower in the litterbag experiment (23-33 kg N ha^{-1}) than in the manure-application experiment (200, 400 and 600 kg N ha^{-1}). Finally, the spatial distribution of the manure within the field plots was not even; there were clods of various sizes in the manure-application experiment.

4.4.5. Residual N recovery from manure

Of the total ANR_F over two growing seasons, up to about 80% of the recovery occurred during the year of manure application. However, in the second year there was still a difference among the manure types in the same order: COV > FRE > COM ($P < 0.05$). This trend was in contrast with Berntsen et al. (2007) and Schröder et al. (2007) who reported that manures with a relatively large first-year ANR_F exhibited relatively small residual N effects. However, our trend was in agreement with the results presented by Paul and Beauchamp (1993) and Eghball and Power (1999) who reported relatively higher first-year as well as residual ANR_F after a single application of FRE compared to COM solid cattle manure. Schröder et al. (2007), on the other hand, found an almost zero ANR_F in the two residual years after a single application of FRE solid cattle manure on sandy grassland. Our observed residual N recovery (2-5% of the original applied N, equivalent to 4-30 kg N ha^{-1}) may seem small from an agronomic point of view at first sight. However, with the farmer's practice of yearly repeated manure applications, this small initial effect may add up to significant cumulative effects after several years (e.g. Schröder 2005). This is supported by Sonneveld and

Lantinga (2010) who found a major contribution to the apparent soil N supply from long-term additions of animal manure N to the soil N pool. Thus, the true N fertiliser value of manure can only be established after taking into account its long-term effects.

The higher stability and content of recalcitrant compounds i.e. lignin in COM manure (Table 4.2) can be considered as favourable for some quality aspects in the long run. For instance, per unit of applied manure it could contribute to a stronger increase in the soil OM content than COV manure. However, the amounts of lignin, DM, C and N lost during the storage phase have to be taken into account for a proper comparison since the evaluation of storage treatments on the basis of equal additions to soil will not be sufficient (Kirchmann and Bernal 1997). Of the total initials, about 34% lignin, 59% DM, 67% C and 46% N were lost during composting in our study, whereas the respective values in case of the COV storage were only 25, 22, 17 and 10%. Therefore, after correcting the lost fractions for their initial contents, amounts of all these parameters remaining at the end of the storage phase were substantially higher in the COV compared to the COM treatment. For example, total amount of lignin was reduced from an initial amount of 514 kg heap^{-1} to 342 kg heap^{-1} after COM (-33%), whereas this was 384 kg heap^{-1} in case of the COV treatment (-25%). After field application, COV manure decomposed faster causing more nutrients to release for plant uptake (Tables 4.3 and 4.4). Because of the increased N supply, this manure resulted in relatively higher crop yields and N uptake (Fig. 4.4) and thus an increased N cycling through the soil-plant-animal continuum. In organic agriculture, where the use of artificial fertilisers is prohibited, it is essential to recycle N to soil and therefore COV storage is superior in this regard. The use of COM manure has proven to be very effective for reclaiming soils with low OM contents and a sparse vegetation cover, that are potentially vulnerable to erosion and desertification (Diaz et al. 1994; Kirchmann and Bernal 1997). However, because of the relatively greater amount of C, N and cell wall content left after covered storage, it is preferable over composting of SCM also for the soil protection.

4.5. Conclusions

This study clearly demonstrated that C and N losses during solid cattle manure storage can be reduced remarkably by covering the heap with a plastic sheet. After field application, manure stored according to this method decomposed faster and more N was available for plant uptake, both in the year of application and the subsequent year as compared to composted manure. This all resulted in an almost three times higher herbage apparent N recovery of the manure N taken from the barn over the two growing seasons. The residual N fertilising effect in the year after application was only up to about 5% of the initial amount of N applied; however, it was twice as high from covered than composted manure. All these findings lead us to conclude that covered storage of solid manure is superior to composting it from a viewpoint of on-farm N recycling. Implementation of this storage technique would provide a promising option to reduce losses and improve crop utilisation of N from solid cattle manure management systems.

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4.7. References

Aira M, Sampedro L, Monroy F (2008) Detritivorous earthworms directly modify the structure, thus altering the functioning of a microdecomposer food web. Soil Biol Biochem 40:2511-2516

Anonymous (1998) NEN 7432 Manure and derivatives. Determination of the contents of dry matter and organic matter (in Dutch). Gravimetric method. Dutch Standardization Institute (NNI), Delft, the Netherlands

Berntsen J, Petersen BM, Sörensen P, Olesen JE (2007) Simulating residual effects of animal manures using 15N isotopes. Plant Soil 290:173-187

Bloem J, Schouten AJ, Sorensen SJ, Rutgers M, van der Werf A, Breure AM (2006) Monitoring and evaluating soil quality. In: Bloem J, Hopkins DW, Benedetti A (ed) Microbiological methods for assessing soil quality. CABI, Wallingford, UK, pp 23-49

Bradford MA, Tordoff GM, Eggers T, Jones TH, Newington JE (2002) Microbiota, fauna, and mesh size interactions in litter decomposition. Oikos 99:317-323

Bremner JM (1965) Organic nitrogen in soil. In: Bartholomew WV, Clark FE (ed) Soil nitrogen. Agronomy Monograph 10, Madison, Wisconsin

Chadwick DR (2005) Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmos Environ 39:787-799

Cusick PR, Powell JM, Kelling KA, Hensler RF, Muňoz GR (2006) Dairy manure N mineralization estimates from incubations and litterbags. Biol Fert Soils 43:145-152

Dence CW (1992) The determination of lignin. In: Lin SY, Dence CW (ed) Methods in lignin chemistry, Springer, Berlin. pp 33-61

Dewes T (1995) Nitrogen losses from manure heaps. Biol Agric and Hortic 11:309-317

Diaz E, Roldln A, Lax A, Albaladejo J (1994) Formation of stable aggregates in degraded soil by amendment with urban refuse and peat. Geoderma 63:277-288

Didden W, Römbke J (2001) Enchytraeids as indicator organisms for chemical stress in terrestrial ecosystems. Ecotox Environ Safe 50:25-43

Eghball B, Power JF, Gilley JE, Doran JW (1997) Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J Environ Qual 26:189-193

Eghball B, Power JF (1999) Phosphorus and nitrogen-based soil and compost application: Corn production and soil phosphorus. Soil Sci Soc Amer J 63:895-901

Gutser R, Ebertseder T, Weber A, Schraml M, Schmidhalter U (2005) Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. J Plant Nutr Soil Sci 168:439-446

Hansen MN, Henriksen K, Sommer SG (2006) Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: Effects of covering. Atmos Environ 40:4172-4181

Houba VJG, Van Der Lee JJ, Novozamsky I, Walinga I (1989) Soil and plant analysis, a series of syllabi, Part 5. Wageningen University, the Netherlands

Huijsmans JFM, Mosquera J, Hol JMG (2007). Ammonia emission during spreading of solid manure (in Dutch). Deskstudie, Report 155. Plant Research International, Wageningen, The Netherlands

Jenkinson DS, Tinsley J (1959) Studies on the organic material extracted from soil and composts. 1. The isolation and characterisation of ligno-proteins from composts. J Soil Sci 10:245-263

Kirchmann H, Bernal MP (1997) Organic waste treatment and C stabilization efficiency. Soil Biol Biochem 29:1747–1753

Kirchmann H (1985) Losses, plant uptake and utilization of manure nitrogen during a production cycle. Acta Agri Scand Suppl 24:1-77

Kirchmann H, Witter E (1989) Ammonia volatilization during aerobic and anaerobic manure decomposition. Plant Soil 115:35-41

Larney FJ, Buckley KE, Hao X, McCaughey WP (2006) Fresh, stockpiled, and composted beef cattle feedlot manure: nutrient levels and mass balance estimates in Alberta and Manitoba. J Environ Qual 35:1844-1854

Levi-Minzi R, Riffaldi R, Saviozzi A (1986) Organic matter and nutrients in fresh and mature farmyard manure. Biol Wastes 16:225-236

MAFF (1986) The analysis of agricultural materials. In: MAFF/ADAS Reference Book 427, 3rd ed, HMSO, London, United Kingdom

Misselbrook TH, Nicholson FA, Chambers BJ (2005) Predicting ammonia losses following the application of livestock manure to land. Bioresour Technol 96:159-168

Mkhabela MS, Gordon R, Burton D, Smith E, Madani A (2009) The impact of management practices and meteorological conditions on ammonia and nitrous oxide emissions following application of hog slurry to forage grass in Nova Scotia. Agric Ecosyst Environ 130:41-49

Muñoz GR, Kelling KA, Rylant KE, Zhu J (2008) Field evaluation of nitrogen availability from fresh and composted manure. J Environ Qual 37:944-955

Parkinson R, Gibbs P, Burchett S, Misselbrook T (2004) Effect of turning regime and seasonal weather conditions on nitrogen and phosphorus losses during aerobic composting of cattle manure. Bioresour Technol 91:171-178

Paul JW, Beauchamp EG (1993) Nitrogen availability for corn in soils amended with urea, cattle slurry, and solid and composted manures. Can J Soil Sci 73:253–266

Persson T, Baath E, Clarholm M, Lundkvist H, Soderstrom BE, Sohlenius B (1980) Trophic structure, biomass dynamics and carbon metabolism of soil organisms in a scots pineforest. In: Persson T (ed) Structure and function of northern coniferous forests-an ecosystem study. Ecot Bull Stockholm 32:419-459

Petersen SO, Lind AM, Sommer SG (1998) Nitrogen and organic matter losses during storage of solid cattle and pig manure. J Agric Sci Camb 130:69-79

Pettygrove GS, Heinrich AL, Eagle AJ (2009) Dairy manure nutrient content and forms. University of California Cooperative Extension. Manure technical bulletin series. (URL: http://manuremanagement.ucdavis.edu, visiting date January 2010)

Römbke J, Hanagarth W, Höfer H, Garcia M, Martius C (2006) Feeding rates of soil organisms at four different forest sites in Amazonia. J Trop Ecol 22:313-320

Rotz CA (2004) Management to reduce nitrogen losses in animal production. J Animal Sci 82:119-137

Rutgers M, Schouten AJ, Bloem J, van Eekeren N, de Goede RGM, Akkerhuis GAJM, van der Wal A, Mulder C, Brussaard L, Breure AM (2009) Biological measurements in a nationwide soil monitoring network. Eur J Soil Sci 60:820-832

Rutgers M, Mulder C, Schouten AJ, Bloem J, Bogte JJ, Breure AM (2008) Soil ecosystem profiling in the Netherlands with ten references for biological soil quality. Report 607604009, RIVM, Bilthoven

Sagoo E, Williams JR, Chambers BJ, Boyles LO, Matthews R, Chadwick DR (2007) Integrated management practices to minimize losses and maximise the crop nitrogen value of broiler litter. Biosyst Eng 97:512-519

Sana J, Soliva M (1987) Composting. Process, systems and applications (original in Spanish). Servei de Medi Ambient, Diputacio de Barcelona, Barcelona, Spain

Schröder JJ, Uenk D, Hilhorst GJ (2007) Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant Soil 299:83-99

Schröder JJ (2005) Manure as a suitable component of precise nitrogen nutrition. In: Proceedings No. 574, International Fertiliser Society, York, UK, pp 1-30

Shah GM, Rashid MI, Shah GA, Groot JCJ, Oenema O, Lantinga EA (2012a) Mineralization and herbage recovery of animal manure nitrogen after application to various soil types Plant Soil doi 10.1007/s11104-012-1347-8

Shah GM, Shah GA, Groot JCJ, Oenema O, Lantinga EA (2012b) Irrigation and lava meal use reduce ammonia emission and improve N utilization when solid cattle manure is applied to grassland. Agric Ecosyst Environ 160:59-65

Sharkey MJ (1970) Errors in measuring nitrogen and dry matter content of plant and faeces material. J Br Grassl Soc 25:289-294

Sheldrick WF, Syers JK, Lingard J (2003) Contribution of livestock excreta to nutrient balances. Nutr Cycling Agroecosyst 66:119-131

Sommer SG, Dahl P (1999) Nutrient and carbon balance during the composting of deep litter. J Agr Eng Res 74:145-153

Sommer SG, Hutchings NJ (2001) Ammonia emission from field applied manure and its reduction-invited paper. Eur J Agron 15:1-15

Sonneveld MPW, Lantinga EA (2010) The contribution of mineralization to grassland N462 uptake on peatland soils with anthropogenic A horizons. Plant Soil 340:357-368

Thomsen IK (2001) Recovery of nitrogen from composted and anaerobically stored manure labelled with 15N. Eur J Agron 15:31-41

Thomsen IK, Olesen JE (2000) C and N mineralization of composted and anaerobically stored ruminant manure in differently textured soils. J Agric Sci 135:151–159

Van Eekeren N, Bommele L, Bloem J, Schouten T, de Goede R, Reheul D, Brussaard L (2008) Soil biological quality after 36 years of ley-arable cropping, permanent grassland and permanent arable cropping. Appl Soil Ecol 40:432-446

Yang HS, Janssen BH (2000) A mono-component model of carbon mineralization with a dynamic rate constant. Eur J Soil Sci 51:517-529

Chapter 5

Irrigation and lava meal use reduce ammonia emission and improve N utilisation when solid cattle manure is applied to grassland

G.M. Shah, G.A. Shah, J.C.J. Groot, O. Oenema, E.A. Lantinga

Abstract

Considerable losses of nitrogen (N) may occur during and after surface-application of solid cattle manure to grassland. These losses are due mainly to the emission of ammonia (NH_3) and represent a threat to the environment. Consequently, N fertiliser value of the manure is reduced. Therefore, adjusted manure application strategies were evaluated in three field experiments focusing on NH_3 emission and herbage N recovery. Fresh, composted and covered solid cattle manures were surface-applied to grassland at a rate of 400 kg N ha^{-1} with or without irrigation and/or lava meal addition. NH_3 emissions were estimated by means of diffusion samplers installed 20 cm above the soil surface for a period of 3 to 4 days. Irrigation (5 mm) immediately after applying fresh manure reduced ($P < 0.05$) NH_3 emission by 30%, whereas it was not effective in the case of composted manure. Irrigation (5 and 10 mm) following application of covered manure reduced ($P < 0.001$) NH_3 emission by 65 and 92%, respectively. Lava meal addition before application at a rate of 80 g per kg manure resulted in an emission reduction ($P < 0.05$) of 46%. The combined use of lava meal and 10 mm irrigation led to a reduction of 97% while apparent recovery of the manure N in herbage increased ($P < 0.05$) from 18 (untreated control) to 26% over three harvests in five months' time. Effects of irrigation were restricted to the first grass harvest only, whereas the positive effects of lava meal were still present in the second harvest. It is concluded that both the use of lava meal as manure additive and irrigation immediately after manure application can reduce NH_3 emission and improve herbage N uptake.

Key words: Solid cattle manure, Irrigation, Lava meal, NH_3 emission, Herbage N recovery

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5.1. Introduction

In the Netherlands, cattle are the main source (~60%) of livestock manure (Luesink et al. 2009). Most of the manure is collected as slurry in cubicle barns, but the proportion of solid manure is increasing due to growing interest of farmers in switching back to straw-based housing systems for reasons of animal health and welfare (Ellen et al. 2007). After excretion in barns, solid cattle manure is usually stockpiled or composted for an extended period of time prior to land application. It is well-known that up to 50% of the initial N_{total} can be lost during storage of solid manure (Kirchmann 1985; Eghball et al. 1997). Attempts have already been made in developing effective solid manure storage techniques to reduce these losses (Chadwick 2005; Sagoo et al. 2007). Recently, Shah et al. (2012) observed that covering solid cattle manure heaps with an impermeable plastic sheet reduced total N losses during storage by 71% compared to uncovered stockpiled heaps. However, imposed strategies which conserve N during storage are known to increase the ammonium (NH_4^+) content that in turn potentially can enhance NH_3 emission after manure application (Amon et al. 1997, 2001). Consequently, the measures taken to reduce N losses during the storage phase will only be beneficial if they are not counterbalanced by higher losses after application.

Land application of manure is a critical step in manure management as it is one of the major sources of NH_3 emission into the air, contributing about 30% to the total emission from Dutch agriculture (Luesink and Kruseman 2007). Huijsmans et al. (2007) concluded that NH_3 emission after application of solid cattle manure to grassland can be up to 100% of the total ammoniacal N (TAN) content. So far, few practices have been identified that reduce NH_3 emissions following land application of solid manure (Sommer and Hutchings 2001; Webb et al. 2010). Rapid incorporation of solid manure into the soil after application is a well-known strategy to reduce NH_3 emissions (Webb et al. 2004, 2010). However, this cannot be practiced easily in (a) soils containing stones or remnants of tree stubs, (b) permanent grassland, (c) farms lacking access to powerful machinery, and (d) situations where soil cultivation can promote wind erosion (McGinn and Sommer 2007; Webb et al. 2010). Therefore, it is crucial to develop other approaches to reduce NH_3 emission for these conditions.

NH_3 emission occurs through mass-transfer of NH_3 from the manure surface to the free atmosphere/air (Pinder et al. 2004). It can be reduced by immobilisation of NH_4^+-N, adsorption of NH_4^+, lowering the pH, and minimising exposure of the manure surface to the air (Sommer and Hutchings 2001; Ndegwa et al. 2008). Jeong and Kim (2005) demonstrated that by adding magnesium (Mg) and phosphate (PO_4) salts during composting of food waste mixtures, NH_4^+ is precipitated into struvite (ammonium magnesium phosphate, $NH_4MgPO_46H_2O$). Therefore, mixing of additives containing Mg and phosphorus (P) compounds such as lava meal (solidified magma) with the manure may lead to struvite formation which could reduce NH_3 emission.

Stimulating infiltration of TAN through the addition of water immediately after solid manure application might be another option to reduce NH_3 emission. In case of cattle slurry, irrigation after surface application has been found to effectively reduce NH_3 emission (Sommer and Hutchings 2001; Sonneveld et al. 2008). However, to our knowledge only a few attempts have been made to study its effect in case of solid cattle manure (Misselbrook et al. 2005; McGinn and Sommer 2007). Therefore, additional research is needed to investigate the effects of irrigation on NH_3 emission after surface-application of solid cattle manure. The combination of irrigation and NH_4^+ conservation through lava meal addition may even lead to a further decrease in NH_3 emission and thus increase the manure's N fertiliser value. Hence, the aim of the current study was to quantify the effects of lava meal and irrigation on NH_3 emission and herbage N recovery from grassland application of solid cattle manure.

5.2. Materials and methods

Three field experiments were conducted at the Organic Experimental and Training Farm Droevendaal, ca. 1 km north of Wageningen, the Netherlands (latitude 55°99'N and longitude 5°66'E). The chemical composition of the soils in the experimental fields is given in Table 5.1 (field A for Expts. 1 and 3, and field B for Expt. 2).

Table 5.1. Chemical properties of the 0-30 cm layer of the experimental fields on sandy soil (85% soil particles > 50 μm).

Field	C_{total}	N_{total}	C/N	NO_3-N	NH_4-N	pH
	($g\ kg^{-1}$)			($mg\ kg^{-1}$)		(KCl)
A	23	1.6	14	1.1	0.1	5.3
B	18	1.2	15	1.6	0.2	5.3

5.2.1. NH_3 emissions from fresh and composted manure (Expt. 1)

This trial was conducted over four days in September 2009 to estimate the effect of irrigation immediately after application of fresh and composted solid cattle manures on NH_3 emissions. The fresh manure was taken directly from the sloping floor barn of the farm where straw was used as bedding material at a daily rate of 5 kg per livestock unit (i.e. 500 kg live weight). The composted manure was produced during a storage period of about seven and a half months, as described by Shah et al. (2012). At the day of manure application, grass was cut to a height of 4 cm and the manures were surface-applied manually in circular plots, each with a diameter of 3 m. Just before application, two composite samples from each manure type were taken and analysed for total N, NH_4^+-N, NO_3^--N, dry matter (DM), and pH (Table 5.2). All the manure analyses were done in fresh samples. Total N was measured after Kjeldahl digestion (MAFF 1986). NH_4^+-N and NO_3^--N were measured in a 1:10 manure/0.01M $CaCl_2$ extract spectrophotometrically by means of segment-flow analysis (Houba et al. 1989). DM was determined after drying the samples at 105°C for 24 hours (Anonymous 1998). The pH was measured in a 1:10 manure/0.01 M $CaCl_2$ extract using a pH meter.

The manures were applied at a rate of 400 kg N ha^{-1} during a period of dry weather. Imposed treatments were: surface-application of fresh manure, surface-application of fresh manure followed by 5 mm irrigation (IRR), surface application of composted manure, surface-application of composted manure followed by 5 mm IRR, control (without manure), and 5 mm IRR applied to the control. The treatments were arranged in a randomised complete block design with two replicates. Irrigation was done immediately (< 10 minutes) after

Table 5.2. Average characteristics of solid cattle manure and amounts of N applied at spreading for the experiments.

Manure	DM	pH	N_{total}	$^aN_{mineral}$	$N_{organic}$	N applied	
						N_{total}	$N_{min.}$
	(g kg^{-1})	($CaCl_2$)	(g kg^{-1}DM)			(kg ha^{-1})	
Expt. 1							
Fresh	189	8.0	27.5	4.3	23.2	400	62
Composted	229	8.4	31.9	4.8	27.1	400	60
Expt. 2 (covered manure)							
Without lava meal	202	8.3	30.5	5.8	24.7	400	76
With lava meal	285	8.2	21.8	4.3	17.5	400	79
Expt. 3							
Covered	180	7.0	30.1	9.5	20.6	400	128

[a] $N_{mineral}$ represents the NH_4^+-N content since NO_3^--N was not present.

manure application using watering cans with spouts. Thereafter, average NH_3 concentration in the air above each plot was determined for 4 consecutive days using diffusion samplers (see section 5.2.4). The assumption was made that NH_3 emissions are proportional to this concentration after correcting for the average background value.

5.2.2. NH_3 emissions and plant N uptake from covered manure (Expt. 2)

This experiment was carried out on a one-year old perennial ryegrass (*Lolium perenne* L.) sward on a sandy soil. Sowing took place in April 2009 at a seed rate of 35 kg ha^{-1}. The pre-experimental treatment consisted of regular cutting of the herbage to a height of 4 cm with the last harvest one day before manure application. On 2 June 2010, covered solid cattle manure was applied with and without irrigation and/or lava meal addition in order to estimate their effects on NH_3 emissions and herbage N uptake. The manure was obtained by storing freshly-collected solid cattle manure for six months (from early December 2009 until the end of May 2010) under an impermeable plastic sheet (anaerobic storage) in the same way as described by Shah et al. (2012). After the storage period, manure was surface-applied manually at an application rate of 400 kg N ha^{-1} in circular plots with a diameter of 3 m. Treatments were: (i) surface-application of manure, (ii) surface-application of lava meal (LM)-mixed manure, (iii) surface-application of manure followed by 5 mm IRR, (iv) surface-application of manure followed by 10 mm IRR, (v) surface-application of LM-mixed manure followed by 5 mm IRR, (vi) surface-application of LM-mixed manure followed by 10 mm IRR, (vii) control (without manure), (viii) LM applied to control, (ix) 5 mm IRR applied to control, (x) 10 mm IRR applied to control, (xi) LM and 5 mm IRR applied to control, and (xii) LM and 10 mm IRR applied to control.

Irrigation was done immediately (< 10 minutes) after manure application in the same way as in Expt. 1. Lava meal (Table 5.3) was included at a rate of 8% of the manure's fresh weight. This inclusion rate was selected after a preliminary trial (results not presented) where effects of applying manure mixed with different rates of lava meal on NH_3 emission were evaluated. Lava meal was mixed gently during weighing of the manure one day prior to its field application, whereas in the control plots it was field-applied at the day of manure application. Just before application, two composite samples from the manure with and without lava meal addition were taken and analysed similar to that in Expt. 1 (Table 5.2). Treatments were arranged in a randomised complete block design with two replicates. Immediately after manure application, average NH_3

Table 5.3. Chemical composition of lava meal[a].

Chemical	Composition ($g\ kg^{-1}$ DM)	Chemical	Composition ($g\ kg^{-1}$ DM)
SiO_2	405	TiO_2	30
Al_2O_3	140	Na_2O	18
CaO	160	P_2O_5	10
Fe_2O_3	120	SO_3	4
MgO	85	K_2O	27

[a] Lava meal "Eifelgold®" was provided by 'lava-union®' Germany. Grey color, powder form and originated from volcanic rocks. It had a cation exchange capacity of 12 cmol kg^{-1} and pH ($CaCl_2$) of 7.84.

concentration in the air above each circular plot was determined over a period of 3 consecutive days using diffusion samplers (see section 5.2.4).

During the whole growing season, grass was harvested three times on the following days: 27 July, 22 September and 1 November 2010. At each harvest, grass was cut to a height of 4 cm above the soil surface using a motor mower with a cutting bar width of 0.9 m. The net area cut for analysis was the inner 1.8 m^2 (2 m × 0.9 m) from each circular plot to avoid border effects. At the end of each harvest, grass from the rest of the circular plots was also harvested to the same height and removed. Fresh herbage yield from each plot was measured in the field and a representative sub-sample of about 200 g was taken with an auger. The samples were oven-dried at 70°C for 48 hours, weighed, ground to pass a 1 mm sieve and analysed for total N content (Sharkey 1970). The N was determined following Kjeldahl digestion of the plant material (MAFF 1986). Afterwards, apparent N recovery (ANR) was calculated as:

$$ANR\ (\%) = 100 \times \frac{(\mathrm{NC_{manured}} \times \mathrm{DM_{manured}}) - (\mathrm{NC_{control}} \times \mathrm{DM_{control}})}{\mathrm{TN_{aplied}}} \qquad (5.1)$$

Where $NC_{manured}$ is herbage nitrogen content (g N (100 g DM)$^{-1}$) in the manured plots, $DM_{manured}$ is herbage dry matter yield (kg ha^{-1}) in the manured plots, $NC_{control}$ is herbage nitrogen content (g N (100 g DM)$^{-1}$) in the unfertilised plots, $DM_{control}$ is herbage dry matter yield (kg ha^{-1}) in the unfertilised plots, and $TN_{applied}$ is total N applied with manure (kg ha^{-1}).

5.2.3. Herbage N uptake from covered manure (Expt. 3)

This trial was conducted on a young perennial ryegrass sward established on a sandy soil (Table 5.1, field A). The grass was sown in September 2008 at a seed rate of 35 kg ha^{-1}. A cleaning cut of the grass was taken in early May 2009 to control weeds. Thereafter, covered solid cattle manure (Table 5.2) described by Shah et al. (2012) was surface-applied manually on 28 May 2009 at a rate of 400 kg N ha^{-1}. Experimental units consisted of 6 m × 3 m plots. Treatments included: (i) surface-application of manure, (ii) surface-application of manure followed by 5 mm IRR, (iii) control (without manure), and (iv) 5 mm IRR applied to the control. Water was applied immediately (< 10 minutes) after manure application which was carried out in the same way as in Expts. 1 and 2. Treatments were arranged in a randomised complete block design with four replicates.

Grass was harvested four times (9 July, 26 August, 29 September and 9 November 2009) during a whole growing season. At each grass harvest, the net area cut for analysis was the inner 5.4 m^2 (6 m × 0.9 m) from each experimental unit to avoid border effects. Grass was harvested and processed in the same way as in Expt. 2 and ANR was calculated using equation 5.1.

5.2.4. Determination of average NH_3 concentration (Expts. 1 and 2)

Immediately after manure application, diffusion samplers were installed to measure NH_3 concentration in the air above each plot (Kirchner et al. 1999). A set of three samplers was installed vertically (12 cm apart, front side downward) at a height of 20 cm above the soil surface in the middle of each plot using a specially designed wooden frame (Fig. 5.1). The minimum distance between the two adjacent plots was kept at 15 m to avoid mutual interference among the treatments (Malgeryd 1998). There were no buildings or trees within a distance of about 100 m from the experimental area. The samplers were operational within 5 minutes after imposing the treatments and exposed for a period of 72 (Expt. 2) or 96 hours (Expt. 1), since by far the greatest part of the emission occurs within the first three days after solid cattle manure application (McGinn and Sommer 2007). In the samplers, NH_3 is trapped on steel grids impregnated with sulphuric acid.

A diffusion sampler consisted of a palm tube (0.041 m long) made of poly vinyl chloride having very little NH_3 adsorption (Shah et al. 2006). The tube was fitted at one end with a poly-ethylene cap with a rim in order to contain two stainless steel grids. These grids were coated with 60 µL of 10% w/v sulphuric acid. This amount of acid has an NH_3 binding capacity of 9.1 µg dissolved in 5 mL

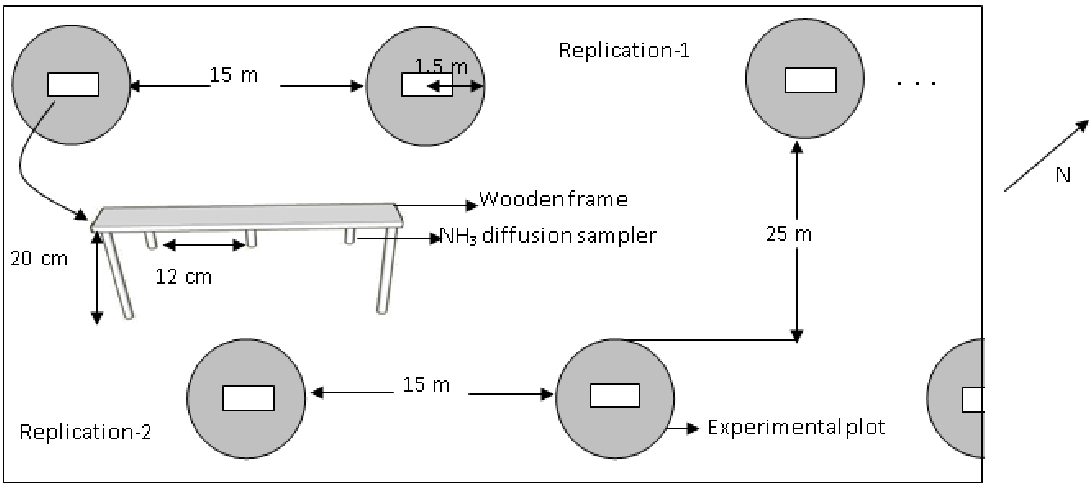

Fig. 5.1. Schematic diagram showing arrangement of plots and diffusion samplers in the field.

of water. The front end of the palm tube was fitted to a transparent poly-ethylene cap with a centre hole (10 mm diameter) to contain a Teflon entrance filter of 12 mm diameter and a pore size of 45 μm. This end was closed with a polyethylene cap (14.5 mm diameter) immediately after preparation until installation as well as after field sampling to avoid adsorption of the ambient NH_3. The procedure for preparation involved a pre-wash of tubes, poly-ethylene caps and steel grids with distilled water. Afterwards, the steel grids were rinsed twice with acetone, dried by laying on clean tissue papers and coated with sulphuric acid.

After the exposure period, all of the installed samplers in field were removed and immediately transported to the laboratory. There, the steel grids were washed with 5 mL of distilled water and the solution was analysed for NH_4^+-N content according to the procedure described in Houba et al. (1989). Subsequently, NH_3 concentration (μg m^{-3}) in the air above each plot was calculated using the following equations developed by Hofschreuder and Heeres (2002).

$$C = \frac{17}{18} \times \frac{Q\,Z}{D\,A\,t} \qquad (5.2a)$$

$$D = (1.1265 \times 10^{-9}) \times \left(\frac{T^{1.75}}{P}\right) \qquad (5.2b)$$

Where C = concentration of NH_3 (μg m^{-3}), Q = sampled amount of NH_4^+ (μg), Z = length of the tube (m), D = diffusion coefficient (m^2 s^{-1}), A = area of the tube (m^2), t = sampling time (s), 17/18 = conversion factor from NH_4^+ to NH_3, T = air temperature (K), and P = air pressure (bar).

Weather data were taken from the nearby weather station of Wageningen University (Table 5.4) and daily evapotranspiration rate was calculated according to the Makkink method (Van Kraalingen and Stol 1997).

5.2.5. Statistical analysis

Expts. 1 and 2 were designed as two-factor mixed models. The factors/treatments in Expt. 1 were manure type (fresh and composted) and irrigation (5 mm), whereas in the case of Expt. 2 these were lava meal (8% of the manure's weight) and irrigation (5 mm and 10 mm). In addition, possible interactions between the factors/treatments in each experiment were tested. For both experiments, the obtained NH_3 concentrations with the three samplers installed in each plot were averaged. Subsequently, the mean values per plot from each of the two replicates were subjected to analysis of variance (ANOVA) using Genstat software (13th Edition, VSN International, Hemel Hempstead, UK) to estimate the significance of the main effects and interactions at 5% probability level. The effects of main treatments and their interactions on herbage N uptake and ANR in Expts. 2 and 3 were tested using ANOVA in Genstat. The factors/treatments in Expt. 3 were manure and irrigation (5 mm). In all the cases differences among the treatments were compared using Tukey test at 5% probability.

Table 5.4. Daily mean weather conditions during the NH_3 measurement period.

Experiment	Day no.	Wind speed ($m\ s^{-1}$)	Temperature (°C)	Humidity (%)	Evapotranspiration ($mm\ day^{-1}$)
1 (year 2009)					
	0	2.0	16.7	91	1.0
	1	2.4	15.6	80	2.1
	2	1.8	14.3	85	1.5
	3	1.9	14.2	86	1.8
	4	2.3	13.6	92	1.3
2 (year 2010)					
	0	3.1	16.0	70	4.5
	1	2.5	16.4	58	4.8
	2	2.2	16.8	62	4.8
	3	1.4	18.8	60	4.9

5.3. Results and discussion

5.3.1. Ammonia emissions

Concentrations of NH_3 above fresh and composted manure without irrigation were not different ($P > 0.05$, Fig. 5.2). This is most likely related to the application of almost equal amounts of NH_4^+-N for both manure types (62 vs. 60 kg ha^{-1}, respectively; Table 5.2). Five mm of irrigation immediately after fresh manure application reduced ($P < 0.05$) NH_3 emission by 30% compared to non-irrigated treatment (Fig. 5.2). However, this level of irrigation was not effective in the case of the composted manure.

As expected, irrigation immediately after land application of covered manure reduced ($P < 0.001$) NH_3 emission remarkably (Fig. 5.3a). Approximately 65% reduction in NH_3 emission was obtained through 5 mm of irrigation, while 10 mm irrigation led to a reduction of 93%. Our observations concur with those of MacGinn and Sommer (2007), who found a 21-57% reduction in NH_3 emission with 6 mm of irrigation immediately after surface-application of solid beef cattle manure compared to when no irrigation was used. Application of water immediately after manure spreading lowers the manure surface temperature, dilutes TAN concentration, and enhances TAN infiltration into (i) the inner side of the manure clumps where it might be safeguarded from exposure to the external temperature and wind, and (ii) the soil where it can be protected against

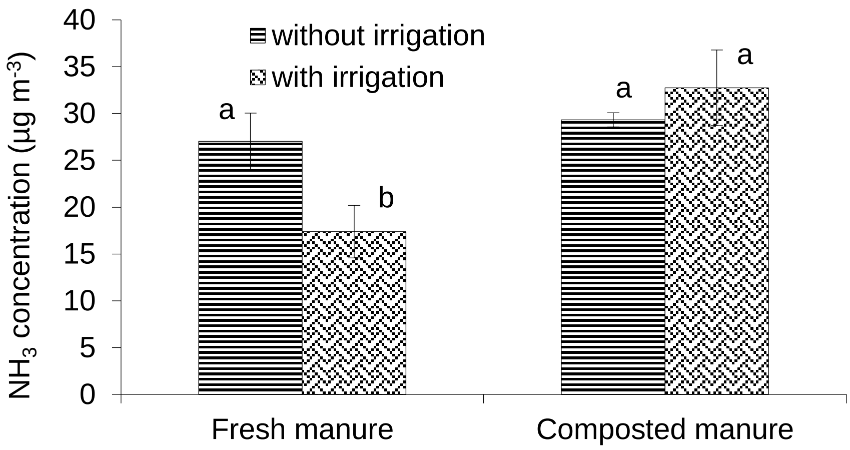

Fig. 5.2. Average ammonia (NH_3) concentration (µg m^{-3}) of the air above plots after application of fresh and composted solid cattle manure with and without irrigation to grassland. The presented values have been corrected from the measured average background value. Error bars represent standard error (±) of mean. Bars having different letters are significantly ($P < 0.05$) different with each other.

volatilization by sorption onto the soil colloids (Sommer and Hutchings 2001; Misselbrook et al. 2005; Mkhabela et al. 2009). However, water absorption and retention capacity of the manure may be crucial in this regard. Visual field investigations shortly after the irrigation event revealed that the clumps of fresh manure were dispersed and their liquid parts were partially washed out into the soil. This did not happen with the clumps of the composted manure which showed more water absorption. In all probability this can be attributed to its higher initial DM content compared to the fresh manure (Table 5.2).

The sole use of lava meal (8% of the manure's fresh weight) before manure application decreased ($P < 0.05$) NH_3 emission by 46% (Fig. 5.3a). In a preliminary trial it was found that by using half of this amount the NH_3 emission decline was about one-third lower (unpublished data). Abatement of NH_3 emission due to lava meal addition may be attributed (i) to adsorption of NH_4^+ by the lava meal as it has a high cation exchange capacity (CEC) of 12 cmol kg^{-1} and (ii) possibly also to precipitation of NH_4^+-N into struvite due to the presence of some P and especially Mg salts in the lava meal (Table 5.3). This is supported by the findings of Zhang and Lau (2007) who found a significant reduction in NH_3 emission during composting of poultry manure due to the addition of Mg and P salts, which they attributed to struvite formation. Struvite is formed by the chemical reaction among free Mg^{+2}, NH_4^+ and PO_4^{-3} at 1:1:1 molar ratio (Ali et al. 2005). The optimum pH for this reaction is between 7 and 9 (Doyle and Parsons 2002; Zhang and Lau 2007). Therefore, the observed pH value of 8.2 in the lava meal amended manure (Table 5.2) may be regarded as favorable for struvite formation.

Addition of lava meal together with irrigation further reduced NH_3 emission up to 97% (Fig. 5.3a). This can be ascribed to their combined effect, i.e. retaining part of the NH_4^+ by the lava meal and improved infiltration of TAN through irrigation. Emission of NH_3 from manure and its reduction with irrigation (5 mm) were higher in 2010 (Fig. 5.3a) than in 2009 (Fig. 5.2). This can be explained by the higher amount of mineral N applied in 2010 (Table 5.2) together with much more favorable environmental conditions for NH_3 emissions (evapotranspiration and wind speed, Table 5.4).

5.3.2. Herbage N uptake

The N uptake by the herbage from manure was significantly higher ($P < 0.05$) with the use of lava meal and/or irrigation compared to untreated manure (Figs. 5.3b and 5.4a). Since there was no effect of irrigation and/or lava meal addition in control (unfertilised) plots, the average value of herbage N uptake for all of the control plots is presented in Figs. 5.3b and 5.4a. Without irrigation and lava meal addition, approximately 18% of the applied manure N_{total} was recovered in the aboveground herbage biomass over three harvests during a growing period of five months in 2010. In the year of application, Schröder et al. (2007) observed a similar ANR (~20%) from surface-applied fresh solid cattle manure to grassland on a sandy soil in the Netherlands over a period of about eight months. In our study, this fraction was increased to 22% and 24% by 5 and 10 mm of irrigation immediately after manure application, respectively (Table 5.5). Also in 2009, five mm of irrigation after manure application resulted in higher ANR (19% of the applied manure N_{total}) compared to no irrigation (14%, Table 5.5) during a growing period of five and a half months. This lower ANR value in 2009 compared to that of 2010 could be attributed to differences in condition of the grass swards at the start of the experiments. In 2009, we started with a young (eight months old) and hollow grass sward with a low tiller density. After the 1st experimental harvest with predominantly reproductive tillers, regrowth was slow. This was accompanied by a relatively high investment of absorbed N in the stubble layer for the formation of new vegetative tillers. In 2010, the grass sward was more than one-year old and well established with a dense stubble and thus resulted in a higher harvestable N uptake.

The herbage recovered 24% of the total amount of N supplied with lava meal amended manure. Combined use of 10 mm irrigation and lava meal further increased the manure N recovery to 26% (Table 5.5). The effects of irrigation on herbage ANR were most pronounced in the 1st grass cut, since differences in herbage N uptake with and without irrigation in the subsequent harvests appeared to be relatively small (Figs. 5.3b and 5.4a). However, significant positive effects of lava meal addition were still apparent in the 2nd grass harvest (Fig. 5.3b). This might have been due to the continued release of NH_4^+ from the struvite which is a slow N-releasing compound (Ali et al. 2005; Zhang and Lau 2007). Lava meal and irrigation (5 and 10 mm) did not have an influence on herbage N use efficiency (NUE, kg DM (kg N uptake)$^{-1}$), since treatment differences in DM yield were absent at a given level of cumulative N uptake (Figs. 5.3c and 5.4b). However, herbage DM production per unit of N uptake was lower in 2010 compared to 2009. This can be ascribed to differences in management of the swards before the start of the experiments. In 2010, the standing herbage was cut one day before manure application with which all the elongated reproductive tillers were removed. Therefore, at the time of the 1st experimental

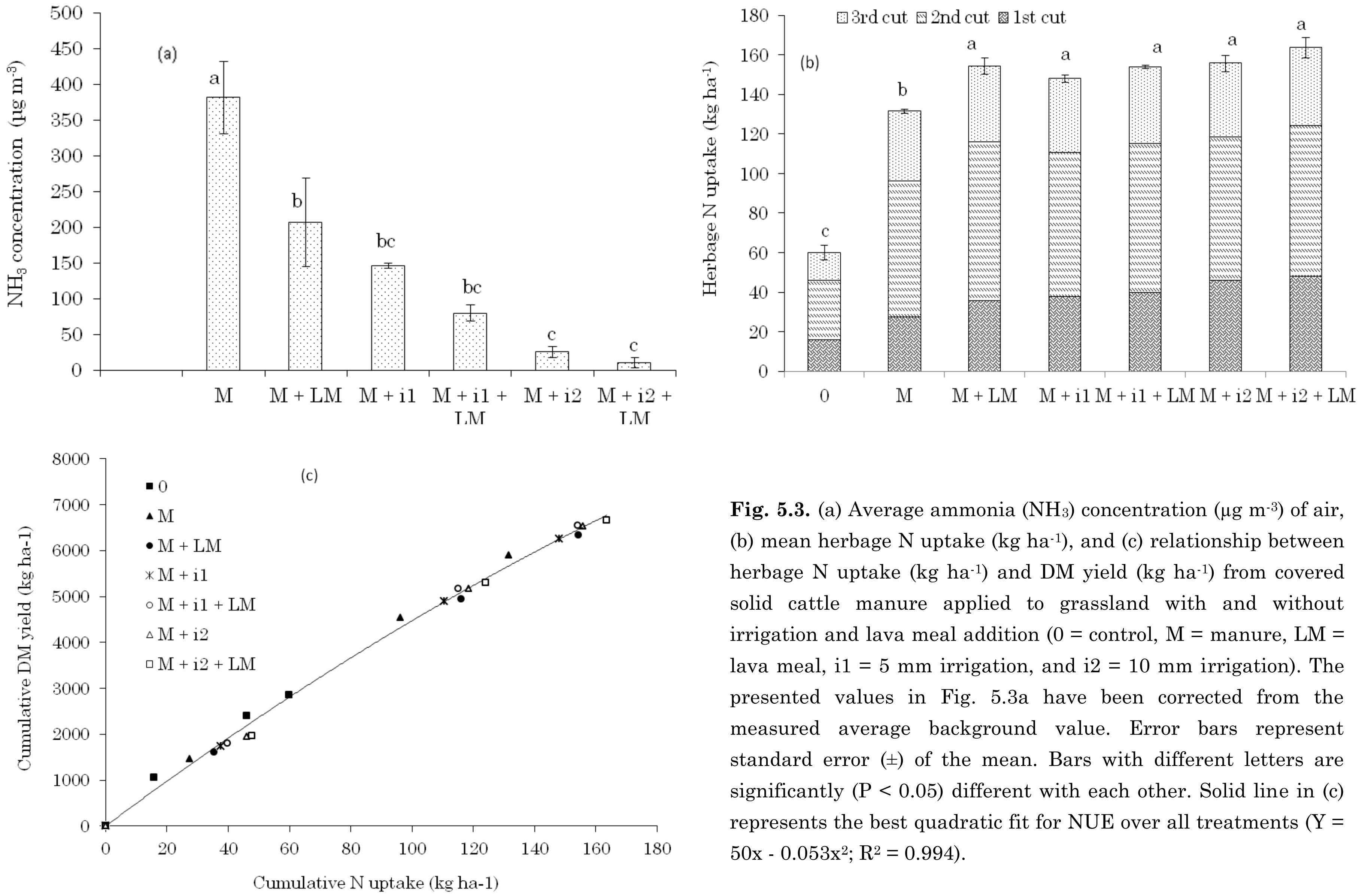

Fig. 5.3. (a) Average ammonia (NH_3) concentration (µg m^{-3}) of air, (b) mean herbage N uptake (kg ha^{-1}), and (c) relationship between herbage N uptake (kg ha^{-1}) and DM yield (kg ha^{-1}) from covered solid cattle manure applied to grassland with and without irrigation and lava meal addition (0 = control, M = manure, LM = lava meal, i1 = 5 mm irrigation, and i2 = 10 mm irrigation). The presented values in Fig. 5.3a have been corrected from the measured average background value. Error bars represent standard error (±) of the mean. Bars with different letters are significantly ($P < 0.05$) different with each other. Solid line in (c) represents the best quadratic fit for NUE over all treatments ($Y = 50x - 0.053x^2$; $R^2 = 0.994$).

Table 5.5. Average apparent nitrogen recovery (ANR) in herbage from covered solid cattle manure amended with and without lava meal, and applied with and without irrigation to grasslands.

Experiment	Treatments		ANR
	Lava meal ($g\ kg^{-1}$ manure)	Irrigation (mm)	(%)
2	0	0	18 (b)
	80	0	24 (a)
	0	5	22 (a)
	80	5	24 (a)
	0	10	24 (a)
	80	10	26 (a)
3	0	0	14 (b)
	0	5	19 (a)

Values with different letters in parenthesis within an experiment are significantly different at $P = 0.05$.

cut nearly all of the grass plants were in the vegetative stage with an average N content of 2.3% in the harvested DM. On the contrary, in the young undeveloped sward of 2009 only a light cleaning cut was taken about one month earlier. Consequently, the grass harvested during the 1st experimental cut was in its reproductive stage with a relatively low average N content of 1.9% in the DM. Moreover, this cut constituted about 50% of the total N uptake (Fig. 5.4a).

Lava meal is a rock powder originating from volcanic rocks. It contains 'pre-cooked' minerals that plants can take up easily. This is potentially an additional advantage of this product. However, the minimum price farmers had to pay for 1 kg of lava meal was about € 0.25 in mid-2011. Therefore, depending on farm infrastructure, irrigation might be a less costly operation. For this purpose, a common liquid manure spreader can easily be used. As an alternative to this, farmers can simply spread the manure just before and/or during a rainfall event. In case of wet field conditions the use of broad low pressure tyres are recommended to avoid sward damage.

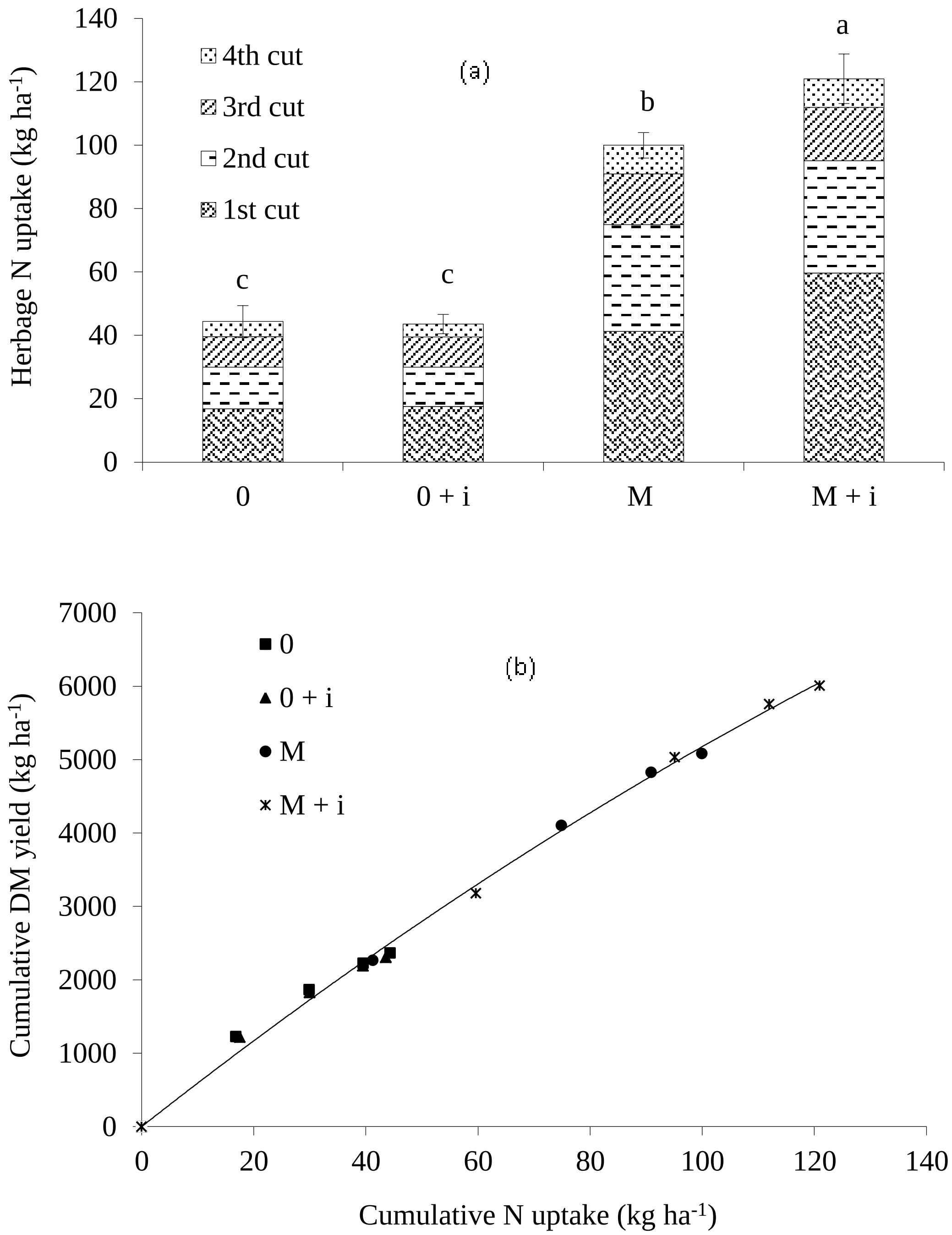

Fig. 5.4. (a) Mean herbage N uptake (kg ha^{-1}) and (b) relationship between herbage N uptake (kg ha^{-1}) and DM yield (kg ha^{-1}) after grassland application of covered solid cattle manure with and without irrigation (0 = control, i = irrigation, and M = manure). Error bars represent standard error (±) of mean of the total herbage N uptake. The bars having different letters are significantly ($P < 0.05$) different with each other. Solid line in (b) represents the best quadratic fit for NUE over all treatments ($Y = 60x - 0.083x^2$; $R^2 = 0.995$).

5.4. Conclusions

The results clearly demonstrated that NH_3 emissions following land application of fresh and covered solid cattle manure were remarkably reduced by using irrigation and/or lava meal addition. Irrigation appeared to be more effective in reducing NH_3 emissions than the addition of lava meal in the case of covered manure. By combining these two strategies an almost 100% reduction could be realised, whereas manure N recovery increased from 18 to 26%. Nevertheless, from a practical viewpoint both strategies are costly and/or time consuming. Therefore, in situations where soil incorporation of manure is not possible or appreciated, land application just before and/or during a rainfall event is the cheapest option to minimise NH_3 emission. Integration of this approach with the anaerobic manure storage strategy can be considered as the best practical option for farmers to reduce losses and improve utilisation of N from solid cattle manure management systems.

5.5. Acknowledgments

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5.6. References

Ali MI, Schneider PA, Hudson N (2005) Thermodynamics and solution chemistry of struvite. J Indian Inst Sci 85:141-149

Amon B, Amon T, Boxberger J, Alt C (2001) Emissions of NH_3, N_2O and CH_4 from dairy cows housed in a farmyard manure tying stall (housing, manure storage, manure spreading). Nutr Cycl Agroecosyst 60:103-113

Amon B, Boxberger J, Amon TH, Zaussinger A, Pollinger A (1997) Emission data of NH_3, CH_4 and N_2O from fattening bulls, milking cows, and during different ways of storing solid manure. In: Voermans JAM, Monteney GJ (ed) Ammonia and odour control from animal production facilities. Elsevier, Amsterdam, the Netherlands, pp 397-404

Anonymous (1998) NEN 7432 Manure and derivatives. Determination of the contents of dry matter and organic matter (in Dutch). Gravimetric method. Dutch Standardization Institute (NNI), Delft, the Netherlands

Chadwick DR (2005) Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmos Environ 39:787-799

Doyle JD, Parsons SA (2002) Struvite formation, control and recovery. Water Res 36:3925-3940

Eghball B, Power JF, Gilley JE, Doran JW (1997) Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J Environ Qual 26:189-193

Ellen H, Groenestein K, Smith M (2007) Emissions from storage of solid manure (in Dutch). Report 58. Animal Sciences Group, Wageningen University, the Netherlands, pp 19

Hofschreuder P, Heeres P (2002) Measurement of NH_3 in ambient air using a modified palms diffusion tube. 3^{rd} version of the protocol for the Interreg study. Meteorology and Air Quality Group, Wageningen University, the Netherlands, pp 14

Houba VJG, Van Der Lee JJ, Novozamsky I, Walinga I (1989) Soil and plant analysis, a series of syllabi, Part 5. Wageningen University, the Netherlands

Huijsmans JFM, Mosquera J, Hol JMG (2007) Ammonia emission during spreading of solid manure (in Dutch). Deskstudy, Report 155. Plant Research International, Wageningen University, the Netherlands, pp 1-26

Jeong YK, Kim JS (2005) Optimum doses of Mg and P salts for precipitating ammonia into struvite crystals in aerobic composting. Bioresour Technol

96:1-6

Kirchmann H (1985) Losses, plant uptake and utilization of manure nitrogen during a production cycle. Acta Agric Scand Suppl 24, pp 77

Kirchner M, Braeutigam S, Ferm M, Haas M, Hangartner M, Hofschreuder P, Kasper-Giebl A, Römmelt A, Striedner J, Terzer W, Thoni L, Werner H, Zimmerling, R (1999) Field intercomparison of diffusive samplers for measuring ammonia. J Environ Monit 1:259-265

Luesink HH, Blokland PW, Bosma JN, Hoogeveen MW (2009) Monitoring manure market. Background documentation 2008 (in Dutch). Report 2008-090, LEI Wageningen University, Den Haag, the Netherlands, pp 129

Luesink HH, Kruseman G (2007) Emission inventories. In: Starmans DAJ, Van der Hoek KW (ed) Ammonia, the case of the Netherlands., Wageningen Academic Publishers, the Netherlands, pp. 45-67

MAFF (1986) The analysis of agricultural materials. In: MAFF/ADAS Reference Book 427, 3rd ed, HMSO, London, United Kingdom

Malgeryd J (1998) Technical measures to reduce ammonia losses after spreading of animal manure. Nutr Cycl Agroecosyst 51:51-57

McGinn SM, Sommer SG (2007) Ammonia emission from land-applied beef cattle manure. Can J Soil Sci 87:345-352

Misselbrook TH, Nicholson FA, Chambers BJ (2005) Predicting ammonia losses following the application of livestock manure to land. Bioresour Technol 96:159-168

Mkhabela MS, Gordon R, Burton D, Smith E, Madani A (2009) The impact of management practices and meteorological conditions on ammonia and nitrous oxide emissions following application of hog slurry to forage grass in Nova Scotia. Agric Ecosyst Environ 130:41-49

Ndegwa PM, Hristov AN, Arogo J, Sheffield RE (2008) A review of ammonia emissions mitigation techniques for concentrated animal feeding operations. Biosyst Eng 100:453-459

Pinder RW, Pekney NJ, Davidson CI, Adams PJ (2004) A process-based model of ammonia emissions from dairy cows: improved temporal and spatial resolution. Atmos Environ 38:1357-1365

Sagoo E, Williams JR, Chambers BJ, Boyles LO, Matthews R, Chadwick D R (2007) Integrated management practices to minimize losses and maximise the crop nitrogen value of broiler litter. Biosyst Eng 97:512-519

Schröder JJ, Uenk D, Hilhorst GJ (2007) Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant Soil

299:83-99

Shah GM, Groot JCJ, Oenema O, Lantinga EA (2012) Covered storage reduce losses and improve crop utilisation of nitrogen from solid cattle manure. Nutr Cycl Agroecosyst 94(2-3):299-313

Shah SB, Grabow GL, Westerman PW (2006) Ammonia adsorption in five types of flexible tubing materials. Appl Eng Agri 22:919-923

Sharkey MJ (1970) Errors in measuring nitrogen and dry matter content of plant and faeces material. J Brit Grassl Soc 25:289-294

Sommer SG, Hutchings NJ (2001) Ammonia emission from field applied manure and its reduction—invited paper. Eur J Agron 15:1-15

Sonneveld MPW, Schröder JJ, De Vos JA, Monteny GJ, Mosquera J, Hol JMG, Lantinga EA, Verhoeven FPM, Bouma J (2008) A whole-farm strategy to reduce environmental impacts of nitrogen. J Environ Qual 37:186-195

Van Kraalingen DWG, Stol W (1997) Evapotranspiration modules for crop growth simulation. Quantitative approaches in systems analysis No. 11, AB-DLO, the Netherlands, pp. 29

Webb J, Chadwick D, Ellis S (2004) Emissions of ammonia and nitrous oxide following rapid incorporation of farmyard manures stored at different densities. Nutr Cycl Agroecosyst 70:67-76

Webb J, Pain B, Bittman S, Morgan J (2010) The impacts of manure application methods on emissions of ammonia, nitrous oxides and crop response-A review. Agric Ecosyst Environ 137:39-46

Zhang W, Lau A (2007) Reducing ammonia emission from poultry manure composting via struvite formation. J Chem Tech Biotechnol 82:598-602

Chapter 6

General discussion

Ghulam Mustafa Shah

6.1. Introduction

Cattle are by far the largest producer of livestock manure, contributing about 60% to the global production (Sheldrick et al. 2003). In Asia and Africa, cattle manure is largely handled as solid mixture of faeces, urine and the bedding material. In Europe and North America, most of the cattle manure is currently being handled as slurry from cubicle barns (Petersen et al. 2007; Ellen et al. 2007). However, in some areas the proportion of solid cattle manure (SCM) is increasing again due to the growing interest of farmers in switching back to straw-based housing systems for reasons of better animal health and welfare (Ellen et al. 2007). In a comparative study in Denmark, Hutchings et al. (2001) concluded that total ammonia (NH_3) emissions from the SCM management chain (deep litter barn, open storage and field application) are roughly two times higher than the slurry management chain (~35 vs. ~18% of the excreted N). Of the total N losses from the SCM management systems, highest losses are likely associated with the storage and application phases (Hutchings et al. 2001). It is well-known that up to about 50% of the initial total N can be lost during storage through traditional stockpiling or composting (Kirchmann 1985; Eghball et al. 1997; Larney et al. 2006), whereas up to about 100% of the initial applied mineral N can be lost after surface application of SCM (Huijsmans et al. 2007). The uncertainties in these estimates are large, whilst the routes of N loss especially from stored SCM are not well understood quantitatively yet. So far, only a few attempts have been made to reduce N losses from the SCM management system, since the focus was on slurry management during the last decades (Webb et al. 2012). Therefore, the search for good SCM management strategies to reduce the losses by improving on-farm N cycling has been the driving force for this thesis.

The main target of my research was to increase the understanding of the factors controlling N losses during storage and after field application, and to develop and test strategies to decrease losses and improve crop utilisation of N from SCM.

This chapter summarises and discusses the main findings of this thesis. Based on the results and their discussion, practical implications are provided and future directions for research are indicated.

6.2. Major findings of the thesis

This section provides a brief overview of the main results. Some of these results give new insights, whereas the others may be seen as confirmation of the earlier findings.

We found a wide variation in first-year N mineralisation and herbage N recovery when a given type of animal manure (SCM, cattle slurry or poultry manure) was applied to diverging soil types (sandy, clay and peat). As expected, N mineralisation and herbage N recovery were lowest from SCM compared to cattle slurry and poultry manure, irrespective of soil type (Chapter 2). From all the manure types, values of both parameters were in the order peat > sandy > clay. The N recovery fraction from fresh SCM both by herbage and maize was low when SCM was stored traditionally (i.e. stockpiling or composting) because of (i) large losses of initial mineral N as well as readily degradable organic N compounds during storage, and (ii) slow mineralisation of organically bound N after field application of the stored manure (Chapters 3 and 4). Up to 31 and 46% of the initial total N was lost during the storage phase through stockpiling and composting methods, respectively (Fig. 6.1; Chapters 3 and 4). In contrast, covering the SCM heap with an impermeable sheet and stockpiling of SCM under a roof reduced the N losses down to 6 and 12% of the initial N content, respectively (Fig. 6.1). Of the total N lost during storage from each treatment, only about one fourth could be traced back as NH_3-N and N_2O-N emissions, and N leaching (Chapter 3). The remainder was unaccounted for and constituted in all probability of the harmless di-nitrogen (N_2) gas.

After field application, covered SCM decomposed faster causing more mineral N to be released for plant uptake as compared to fresh and composted SCM (Chapter 4). Together with its higher initial mineral N content, this resulted in higher levels of crop apparent N recovery (ANR) as compared to the fresh, stockpiled, composted and roofed SCM (Chapters 3 to 4). When the N losses during storage were taken into account to arrive at the crop ANR of the collected N from the barn, an almost three times higher value was observed from covered SCM compared to composted SCM (21 vs. 7% on grassland, and 37 vs. 13% on arable (maize) land; Chapters 3 and 4). The residual N fertilising effect on grassland in the second year was only up to 5% of the applied N. However, it was about twice as high from covered than composted SCM (Chapter 4).

Use of lava meal as SCM additive, and irrigation (simulated rainfall) immediately after surface application of SCM, reduced NH_3 emissions impressively (Chapters 3 and 5). By combing these two practices on grassland an almost 100% reduction in NH_3 emission was realised, whereas herbage ANR increased from 18 to 26% over a growing period of five months (Fig. 6.1; Chapter

5). Incorporation of covered SCM just before sowing of maize resulted in an ANR value of 39% of the applied N, whereas this fraction was 20, 29 and 31% in case of composted, stockpiled and roofed SCM, respectively (Chapter 3).

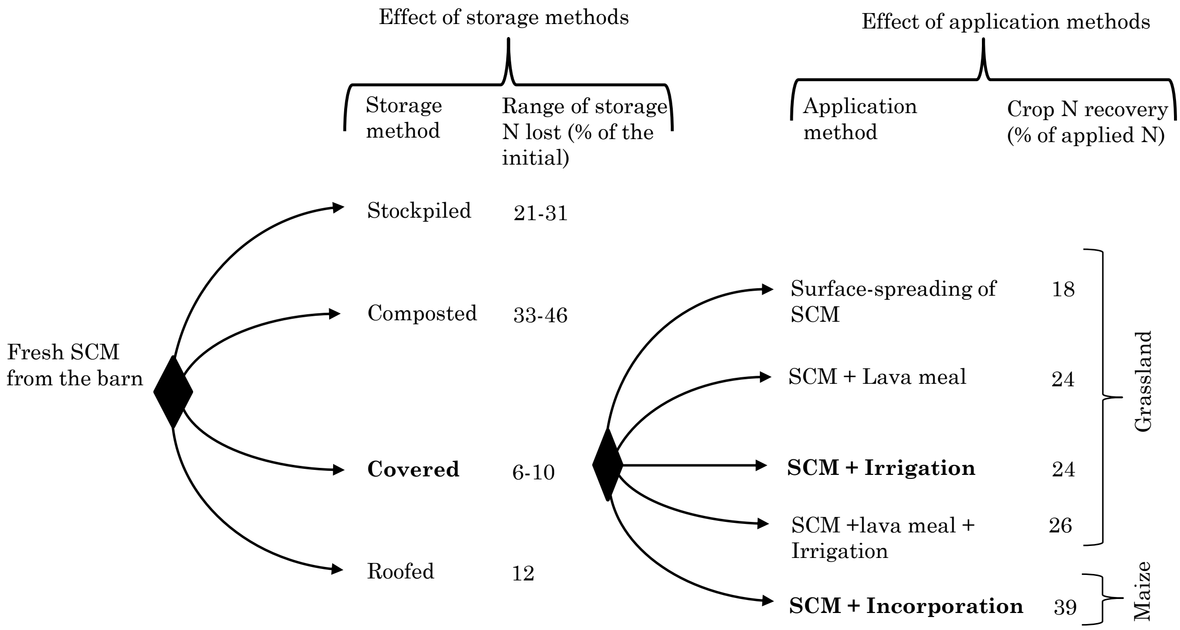

Fig. 6.1. Schematic diagram showing the fractions of N in SCM which were lost during storage depending on storage method and apparently recovered by the two crops (grassland herbage and arable maize) as affected by application method.

6.3. Discussion

6.3.1. Understanding the SCM heap N balance

The N balances from the stockpiled, composted, roofed and covered heaps revealed that only between 19 and 32% of the total storage N losses could be traced back as NH_3-N, N_2O-N and/or N leaching (Chapter 3). These are in the range of 8 to 62% as observed by Sommer and Dahl (1999). However, by far the greater part of the total N losses was unaccounted for and constituted in all probability of harmless N_2 gas, which is the end-product of denitrification (Petersen et al. 1998; Harper et al. 2000; Chadwick 2005). Total N_2O emission and N leaching during our study constituted only about 0.5 to 6% of the total N losses. The source of the N_2O is not known; it may originate from nitrification, nitrifier denitrification, denitrification and chemical denitrification (Van Cleemput 1998; Harper et al. 2000; Kool et al. 2011).

Some might argue that possible uncertainties in SCM sampling and analysis can possibly overestimate the absolute heap N losses and thereby can also partially explain the discrepancy between measured losses and the losses calculated from the mass balance method (e.g. Martin and Dewes 1992). No doubt it is rather difficult to take representative samples from a bulk of SCM because of its great heterogeneity. However, I estimated absolute N losses by two different sampling methods: manually by picking small quantities from various locations of a heap and using the litterbag technique, and the results revealed a good agreement between the two methods (Chapter 3). For instance, loss of about 6% of the initial N from covered and 12% from roofed heaps was observed through both sampling methods. This indicates the absence of sampling effects on the estimated N balance and thereby the fraction of N losses unaccounted for.

6.3.2. Need for proper SCM storage methods and application techniques

Covering of SCM heaps with an impermeable sheet appeared to be the most effective method to decrease storage N losses. The reasons are two-fold: it blocks air circulation through the heap and it creates near-anaerobic conditions. These together slow down microbial decomposition processes leading to only limited increases in heap temperature (Chapter 3). Consequently, production of NH_3 and greenhouse gases is restricted in the covered heaps. Additionally, the sheet forms a physical barrier to the emission of these gases from the heap into the atmosphere. The leaching losses were reduced by almost three times through protection of SCM heap against precipitation either by its covering with an impermeable sheet or its formation under a roof (Chapter 3). Although stockpiling of SCM under a roof significantly reduced overall total N losses, NH_3 and N_2O emissions were much higher as compared to stockpiling of SCM in the open air. This was in all probability due to relatively higher microbial activities especially in the top layer as a result of oxygen supply through its open and porous surface, which increased the temperature and thereby the emission of these gases (Chapter 3). In contrast, the stockpiled heaps in the open air were subjected to the exposure of weather (wetting and drying), which led to the formation of a surface crust and thus creating a physical barrier to NH_3 and N_2O emissions. In case of the composted heaps, turning operations increased (i) air exchange, which stimulated aerobic decomposition processes and thereby the emission of these gases, and (ii) water infiltration from rainfall by loosening the heap and thereby the N leaching (Chapter 3). In view of the above discussion I conclude that covering the SCM heap with an impermeable sheet is by far the best option to conserve N during the storage phase. From a cost perspective, covered storage is a relatively cheap option since it requires only an impermeable sheet i.e. plastic, which can be used several times depending on its quality and handling. In contrast, composting needs extra costs for labour and energy during the turning operations.

Additionally, the N conservation together with the slow mineralisation of organically-bound N during covered storage increased the mineral N content of the SCM at the end of the storage period. This in turns increased the crop N recovery, but also might have led to compensatory N losses through increased NH_3 emissions during or after field application, if left unmanaged (Sagoo et al. 2007). Here the question would be "what are the benefits of conserving N through covered storage if these are counterbalanced by the increased NH_3 emissions after field application"? Application of covered SCM during or just before a predicted rainfall will greatly reduce NH_3 emissions (Chapter 5). Rainfall or irrigation lowers surface temperature of the SCM clumps and will increase infiltration of total ammoniacal N (TAN) into the inner side of the manure clumps and the topsoil. In addition, it results in direct contact of SCM with soil particles by facilitating its dispersion. The infiltration of TAN in the soil largely depends on (i) irrigation or rainfall volume, (ii) dry matter (DM) content of the applied SCM which determines its water absorption and retention capacity (Chapter 5), and (iii) soil characteristics i.e. moisture content and texture (Meisinger and Jokela 2000). A low DM content facilitates quick infiltration of manure TAN into the soil, where it is adsorbed on soil collides or immobilised by the soil microbes and thus reducing the possibility of gaseous N emissions. This "infiltration" and "soil contact" concept explains why solid manure has greater NH_3 emission per unit of mineral N applied than liquid manure as observed by Menzi et al. (1997). It was observed that 5 mm of simulated rainfall reduced NH_3 emissions after spreading of fresh SCM by 30%, and of covered SCM by 65%, whereas this level of rainfall was not sufficient to reduce the emission in case of composted SCM with a relatively high DM content (Chapter 5). Increasing the level of simulated rainfall to 10 mm after surface spreading of covered SCM reduced NH_3 emissions by 93%. All this led me to conclude that application of SCM during or just before a predicted moderate rainfall event is a good option to maximise the effects of covered storage. In the absence of rainfall, irrigation is recommended, which can be a relatively cheap option provided that water is available at low cost and a suitable irrigation infrastructure is available. Relatively cheap liquid manure spreader or slurry tank can be used for this purpose.

Addition of lava meal to SCM a few days before application will reduce NH_3 emissions by adsorption and precipitation of NH_4^+-N (Chapter 5). Lava meal is produced from volcanic rocks and contains mineral nutrients, which can be easily taken up by the plants. Therefore, it can also be used as mineral supplement for the soils. By mixing it with SCM before application, farmers can have dual benefits: supply of mineral nutrients and reduction of NH_3 emission. However, depending on the farm infrastructure use of lava meal is a rather costly operation since the price of one kg of lava meal was about € 0.25 in mid-2011. In addition, mixing lava meal with SCM can be both laborious and energy-intensive, and is likely also associated with emissions (e.g. NH_3). Therefore, I strongly recommend to apply it already in the straw-bedding of the barn. This would recapture the investment through (i) less work for the farmer, (ii) reduction of N losses also during the housing and storage phases, and (iii) a higher crop N utilisation of barn-produced SCM.

6.3.3. Need to increase N recovery from SCM

After field application, covered SCM decomposed faster than composted manure causing more mineral N to be released for plant uptake. Consequently, crop ANR was greater from the covered SCM, both in the year of their application and the year thereafter (Chapter 4). Crop ANR and DM yields from covered SCM can be further increased by (i) its rapid incorporation in non-vegetated soils i.e. arable land and (ii) its application just before a predicted rainfall and/or use of lava meal as additive in case of vegetated soils i.e. grassland (Fig. 6.1). Interestingly, values of both these crop parameters were higher in the former case. The plausible reasons behind this are: (i) relatively low gaseous N emissions after SCM incorporation into the soil with respect to its surface application during rainfall or with lava meal, (ii) increased soil biological activities and net N mineralisation as a result of soil cultivation, and (iii) higher demand of external N because of the greater biomass of maize as compared to ryegrass. In addition to this, SCM and soil management, type of soil can have a great influence on net N mineralisation and crop N recovery (Chapter 2). However, a typical value of plant available N from SCM (i.e. 25% of the applied N) during one growing season is currently communicated with farmers in fertiliser recommendation schemes, irrespective of soil type and storage method. I found that in reality this value varies widely when SCM is applied to different soil types, i.e. peat, sandy and clay (Chapter 2). Highest total herbage ANR (50% of the applied N) was observed in peat soil, which had the highest N delivering capacity, as reflected in the plant

N uptake from unfertilised pots. The relative high ANR suggest that the SCM mineralised faster when added to the peat soil than to the soils with a relatively low native soil N mineralisation rate (see also Magdoff 1978). The high net N mineralisation and herbage ANR in the peat soil is ascribed to the long-term (> 50 years) organic inputs, e.g. animal manure, ditch sludge and crop residues, on the dairy farm where this soil was collected (Sonneveld and Lantinga 2010). These repeated inputs led to a build-up of young soil organic matter including young organic N thus increasing the potential for N mineralisation (e.g. Langmeier et al. 2002). Between the clay and sandy soils, both having similar N delivering capacities in our case, total herbage ANR was lower in the clay soil (15 vs. 25% of the applied N), which is probably due to the increased immobilisation and fixation of ammonium-N by its inherited higher clay content. In view of these results, I strongly advise to provide in the near future soil-specific SCM recommendations in order to efficiently utilise its available N.

Application of SCM can cause residual N effects after the year of its application since the decomposition of the added organic material takes many years (Chapter 4; Gutser et al. 2005; Schröder et al. 2007; Muñoz et al. 2008). On sandy grassland, I found that the residual N effect during the second year was only 5% of the applied N. However, there was still a difference among the manure types in the order: covered > fresh > composted SCM ($P < 0.05$; Chapter 4). Schröder et al. (2007), on the other hand, found an almost zero apparent N recovery in the two residual years after a single application of fresh SCM on sandy grassland. Our observed residual N recovery (4-30 kg N ha^{-1}) may seem small from an agronomical viewpoint, but this small initial effect may turn into a significant cumulative effect after several years of repeated SCM applications. Therefore, the residual N contribution from earlier SCM inputs should also be realised and communicated to farmers in order to avoid overdoses of N and risks for N losses.

Relatively greater decomposition and N release, both during the year of application and the year thereafter from covered SCM than composted SCM, indicate preferences by the soil biota community for the former material, in all probability due to the greater fraction of easily degradable compounds (Chapter 4). Also, more degradable compounds will remain in SCM after covered storage with respect to its composting. This implies that covered SCM will also have more scope in improving soil biology and functioning, which in turn can increase the soil fertility and thereby on-farm N cycling through the soil-plant-animal continuum as compared to the traditional stockpiling or composting methods.

Composted SCM has been considered as a useful source for reclaiming soil with low organic matter content and a sparse vegetation cover, which can be highly vulnerable to erosion and desertification (Diaz et al. 1994; Kirchmann and Bernal 1997). However, because of (i) the greater amount of total C, N and cell wall contents (lignin, cellulose and hemicellulose) left in SCM after covered storage, and (ii) their expected greater input through crop residues as a result of increased crop yields, I strongly suggest to prefer it over composted SCM even if the main concern is soil protection rather than crop production (Chapter 4).

6.4. Practical implications of the research

6.4.1. For reducing environmental pollution and improving N cycling

Covering SCM heaps with an impermeable sheet is the best option to remarkably reduce storage C and N losses (Chapters 3 and 4). For instance, in the Netherlands, about 2 million Mg of SCM is stored currently for a certain period of time prior to field application (Ellen et al. 2007). On average, SCM contains 6.4 g kg^{-1} total N (Blanken et al. 2006). Consequently, 12000 Mg N is being stored annually. Taking into account the N loss fraction from traditional stockpiling and composting (Chapter 4), about 3720 to 5520 Mg N is being lost each year. With the adaptation of the proposed covering method, about 2520 to 4320 Mg of N can be saved annually during the storage phase. Covering decrease two loss routes at once: (i) gaseous emissions to air and (ii) leaching losses to groundwater and surface waters. Currently, there are regulations for covering slurry stores for example in the Netherlands and Denmark, however, it is strongly recommended to introduce such kind of practices also for SCM heaps.

Covered storage will retain much of the excreted N in SCM, thereby increasing the amount of N applied to the soil. Moreover, its higher mineral N content and the readily degradable nature of the organic N will result in substantially higher crop N utilisation and yields compared to fresh SCM taken from the barn or stored under conventional methods (Chapters 3 and 4). Integration of the covered storage with effective application strategies (i.e. irrigation, lava meal addition and rapid soil incorporation) will provide by far the best practical option to reduce losses and improve utilisation of N from SCM, thereby improving on-farm N cycling. This is especially important in (i) farming systems of the developing countries and (ii) organic farming both in the developed and developing world, where efficient utilisation of N from manure is indispensable.

Taking care of soil health would increase farm profitability by enhancing nutrient release for crop production. Adding C and N to soil is beneficial for a wide range of the soil physical, chemical and biological properties (Cantab 2009). I suggest that covered storage allows recycling of a larger proportion of the excreted C and N to the soil when compared to other storage methods by substantially reducing their losses in the storage phase (Chapters 3 and 4). Additionally, because of the increased N supply, covered SCM results in higher crop yields and thus a greater input of C and N through crop residues. These can trigger the activity and abundance of the soil organisms and thus the soil biology to some extent.

6.4.2. Key management actions

Based on the findings of this study the following key management actions are proposed to improve on-farm N cycling:

- If economically attractive, apply lava meal to straw-beddings in the barn (Chapter 5)
- Store the barn-produced SCM under an impermeable sheet (Chapters 3 and 4)
- Adjust soil-specific SCM application rates taking into account potential available N (Chapter 2) and degradability of organic N compounds (Chapter 4)
- In situations where incorporation is not feasible, spread SCM just before a predicted rainfall event or apply irrigation otherwise (Chapter 5)
- Take into account the expected residual N contribution from earlier SCM inputs when determining the SCM application rate (Chapter 4)

All of the above management measures have great potential to reduce losses and improve utilisation of N from SCM. Their adoption can help to (i) restrict the increase in environmental pollution, (ii) achieve the policy objectives of reducing NH_3 and greenhouse gaseous emission from animal manures, and (iii) increase N fertiliser value of SCM. Along with Africa, this efficient N utilisation from the manure is indispensable for the south Asian countries like Pakistan, Nepal, Bangladesh and India, where the use of animal manure as fertiliser source is increasing in response to the (i) low availability and increasing price of chemical fertilisers, and (ii) increasing trend towards organic farming.

6.5. Weaknesses in my research and suggestions for future research

One of the aims of this thesis was to increase the understanding and investigate the effects of various SCM storage methods on the magnitude of C and N loss pathways. Firstly, the estimations of gaseous emission (i.e. NH_3-N, N_2O-N, CH_4-C and CO_2-C) were done through the measurements at discrete points rather than continuous measurements, whereas emission of N_2 could not be measured at all. In this way the emission rates between the two measuring points were assumed to be the same, irrespective of the day and night. The emission rates are usually expected to be low at night. Secondly, the emissions measurements together with N leaching were done from one replication due to the practical constraints. However, estimation of total N losses was done from all three replicates. I think, both these can potentially influence estimation of the emission totals and thereby the fractions of C and N losses unaccounted for. The future studies should avoid such kind of limitations.

On the basis of the results of this study, I conclude that further work is needed for a better understanding of the processes involved and the optimisation of strategies to improve on-farm N cycling. The main recommendations as a follow-up of this thesis are:

- There is a need to develop methods for continuous measurement of all the above mentioned gases for a better quantitative assessment of C and N loss routes. So far, no easy applicable and reliable methods exist for direct measurement of N_2 losses and therefore it provides food for thought to agricultural engineers to develop methods for its measurement.
- Covered storage reduced both C and N losses remarkably when compared to composting, but there is a need to investigate its effects on viability of weed seeds and human pathogens.
- Although crop uptake provided a good integration of the N availability over time, examining long-term effects of various storage and application methods of SCM are needed by quantifying (i) soil processes governing organic matter breakdown and the N mineralisation-immobilisation balance when applied to diverging soil types, and (ii) soil biological parameters i.e. population and activities of soil mico-, meso- and macrofauna.

6.6. References

Blanken K, Evers A, Ferwerda R, Hollander CJ, Kasper G, de Koning K, van Middelkoop J, Ouweltjes W, Slaghuis B, Verstappen J, Visscher J, Wemmenhove H (2006) Handbook Melkveehouderij (in Dutch). Roodbont, Zutphen, the Netherlands

Cantab GAMA (2009) Soil carbon and organic farming- A review of the evidence on the relationship between agriculture and soil carbon sequestration, and how organic farming can contribute to climate change mitigation and adaptation (report). Soil association, UK pp. 212

Chadwick DR (2005) Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmos Environ 39:787-799

Diaz E, Roldln A, Lax A, Albaladejo J (1994) Formation of stable aggregates in degraded soil by amendment with urban refuse and peat. Geoderma 63:277-288

Eghball B, Power JF, Gilley JE, Doran JW (1997) Nutrient, carbon, and mass loss during composting of beef cattle feedlot manure. J Environ Qual 26:189-193

Ellen H, Groenestein K, Smith M (2007) Emissions from storage of solid manure (in Dutch). Animal Sciences Group, Wageningen University, The Netherlands, pp 1-19

Gutser R, Ebertseder T, Weber A, Schraml M, Schmidhalter U (2005) Short-term and residual availability of nitrogen after long-term application of organic fertilizers on arable land. J Plant Nutr Soil Sci 168:439-446

Harper LA, Sharpe RR, Parkin TB (2000) Gaseous nitrogen emissions from anaerobic swine lagoons: Ammonia, nitrous oxide, and dinitrogen gas. J Environ Qual 29:1356-1365

Huijsmans JFM, Mosquera J, Hol JMG (2007) Ammonia emission during spreading of solid manure (in Dutch). Deskstudy, Report 155. Plant Research International, Wageningen University, the Netherlands, pp 1-26

Hutchings NJ, Sommer SG, Andersen JM, Asman WAH (2001) A detailed ammonia emission inventory for Denmark. Atmos Environ 35:1959-1968

Kirchmann H (1985) Losses, plant uptake and utilization of manure nitrogen during a production cycle. Acta Agri Scand Suppl 24:1-77

Kirchmann H, Bernal MP (1997) Organic waste treatment and C stabilization efficiency. Soil Biol Biochem 29:1747–1753

Kool DM, Dolfing J, Wrage N (2011) Nitrifier denitrification as a distinct and significant source of nitrous oxide from soil. Soil Biol Biochem 43:174-178

Langmeier M, Frossard E, Kreuzer M, Mader P, Dubois D, Oberson A (2002) Nitrogen fertilizer value of cattle manure applied on soils originating from organic and conventional farming systems. Agronomie 22:789-800

Larney FJ, Buckley KE, Hao X, McCaughey WP (2006) Fresh, stockpiled, and composted beef cattle feedlot manure: nutrient levels and mass balance estimates in Alberta and Manitoba. J Environ Qual 35:1844-1854

Magdoff FR (1978) Influence of manure application rates and continuous corn on soil-N. Agron J 70:629-632

Martins O, Dewes T (1992) Loss of nitrogenous compounds during composting of animal wastes. Bioresour Technol 42:103-111

Menzi H, Katz P, Frick R, Fahrni M, Keller M (1997) Ammonia emissions following the application of solid manure to grassland. In: Jarvis SC, Pain BF (ed) Gaseous nitrogen emissions from grasslands, CAB International, Wallingford, pp 265–275

Meisinger JJ, Jokela WE (2000) Ammonia volatilization from dairy and poultry manure. In: managing nutrients and pathogens from animal agriculture, *NRAES-130*, natural resource, agriculture, and engineering ervice (NRAES), Cooperative extension, Ithaca NY, pp 334-354

Muñoz GR, Kelling KA, Rylant KE, Zhu J (2008) Field evaluation of nitrogen availability from fresh and composted manure. J Environ Qual 37:944-955

Petersen SO, Lind AM, Sommer SG (1998) Nitrogen and organic matter losses during storage of solid cattle and pig manure. J Agric Sci Camb 130:69-79

Petersen SO, Sommer SG, Béline F, Burton C, Dach J, Dourmad JY, Leip A, Misselbrook T, Nicholson F, Poulsen HD, Provolo G, Sørensen P, Vinnerås B, Weiske A, Bernal M-P, Böhm R, Juhász C, Mihelic R (2007) Recycling of livestock wastes and other residues: a whole-farm perspective, Livest Sci 112:180–191

Sagoo E, Williams JR, Chambers BJ, Boyles LO, Matthews R, Chadwick DR (2007) Integrated management practices to minimize losses and maximise the crop nitrogen value of broiler litter. Biosyst Eng 97:512-519

Schröder JJ, Uenk D, Hilhorst GJ (2007) Long-term nitrogen fertilizer replacement value of cattle manures applied to cut grassland. Plant Soil 299:83-99

Sheldrick W, Syers JK, Lingard J (2003) Contribution of livestock excreta to nutrient balances. Nutr Cycl Agroecosyst 66:119-131

Sommer SG, Dahl P (1999) Nutrient and carbon balance during the composting of deep litter. J Agr Eng Res 74:145-153

Sonneveld MPW, Lantinga EA (2010) The contribution of mineralization to grassland N uptake on peatland soils with anthropogenic A horizons. Plant Soil 340:357-368

Van Cleemput O (1998) Subsoils: Chemo- and biological denitrification, N_2O and N_2 emissions. Nutr Cycl Agroecosyst 52:187-194

Webb J, Sommer SG, Kupper TH, Groenestein K, Hutchings NJ, Eurich-Menden B, Rodhe L, Misselbrook TH, Amon B (2012) Emissions of ammonia, nitrous oxide and methane during the management of solid manures. Sustain Agric Rev 8:67-107

Summary

Summary in English

Background and objectives

The number of domesticated cattle in the world has steadily increased during the last decades, and thereby also the amount of manure produced annually. The excrements of grazing cattle are dropped in pastures and left unmanaged, but that of confined and housed cattle are collected and managed. The collected manure is often a variable mixture of urine, faeces, bedding material and spoiled feed and (drinking) water. On most modern farms, excrements are usually collected in leak-tight storages and handled as slurry: a mixture of urine, faeces and spoiled water. However, on a significant fraction of farms, cattle excrements are 'source-separated' in a liquid fraction and a solid fraction. The solid cattle manure (SCM) is usually a mixture of faeces and bedding material with some absorbed urine. The production of SCM is increasing due to the renewed interest in straw-based housing systems for better animal health and welfare. It has been observed that a significant loss of N can occur, especially from the storage and application phases of the SCM management chain. This N loss pollutes the air, groundwater and surface waters, and also reduces its N fertiliser value. Thus the challenge is to develop an effective SCM management system that retains as much of the excreted N in the system as possible, and thereby improving on-farm N cycling through the cattle-manure-soil-crop continuum **(Chapter 1)**. The main objective of this PhD thesis research was to increase the understanding of the factors controlling N losses during storage and after field application, and to develop and test strategies to decrease N losses and improve crop utilisation of N from SCM. The specific objectives were:

- To study the interactions between a number of animal manures and soil types on N mineralisation and plant N recovery **(Chapter 2)**
- To investigate the effects of storage conditions on (i) magnitude and pathways of C and N losses during storage of SCM, and (ii) crop apparent N recovery (ANR) and DM yield **(Chapter 3)**
- To examine manure disappearance rates, N release pattern and herbage ANR during the year of application and the year thereafter from surface applied SCM subjected to different storage conditions **(Chapter 4)**, and
- To analyse the effect of various application strategies on NH_3 emission and/or crop ANR from applied SCM to grassland and arable (maize) land **(Chapters 3 and 5)**

To pursue these objectives a pot experiment in a glasshouse **(Chapter 2)** and a number of field experiments **(Chapters 3 to 5)** were conducted on experimental facilities of Wageningen University, the Netherlands. The pot experiment dealt with net N mineralisation and herbage ANR from SCM, cattle slurry and poultry manure, all applied to peat, sandy and clay soils. The field experiments examined (i) total C and N losses from stockpiled, composted, covered and roofed SCM heaps, (ii) manure decomposition, N release and herbage ANR after surface application of fresh and stored SCM on grassland, and (iii) the effects of irrigation and soil incorporation after SCM application, and lava meal as an additive on NH_3 emission and/or crop ANR by grassland herbage or arable maize.

Major findings of the thesis

Results of the pot experiment showed that net N mineralisation and herbage ANR varied as function of manure storage method and soil type. Irrespective of the manure types, net N mineralisation and herbage ANR were highest in peat soil, which was characterised by the greatest N delivering capacity. Between the clay and sandy soils, both having similar N delivering capacity, net N mineralisation and herbage ANR were lower in the clay soil than in the sandy soil, likely because of immobilisation and fixation of ammonium-N by its inherited higher clay content. On each soil type, ANR was lower from SCM than cattle slurry and poultry manure **(Chapter 2)**. The N recovery fraction was low when SCM was stored traditionally (i.e. stockpiling or composting) due to (i) loss of the initial mineral N content and readily degradable organic N compounds, and (ii) conversion of part of the remaining N into more stable forms as compared to that originally present before storage. Up to 31% of the initial total N from the stockpiled and 46% from the composted SCM heaps were lost during a period of about four months. Covering and roofing of SCM heaps reduced the losses down to 6 and 12%, respectively. Of the total N losses from each storage method, only about one fourth could be traced back as NH_3-N and N_2O-N emissions, and/or N leaching. The remainder could not be accounted for and constituted, in all probability, of harmless N_2 gas. Of the total measured gaseous and liquid N losses together, N leaching contributed the most. The leaching N losses were reduced by almost three times through protection of SCM heap against precipitation either by its covering or roofing when compared to its stockpiling or composting in the open air. Although stockpiling of SCM under a roof significantly reduced overall total N losses, NH_3 and N_2O emissions were much higher as compared to stockpiling of SCM in the open air. Composting of SCM resulted in higher gaseous N emissions as well as N leaching with respect to the other storage methods. In view of these finding I conclude that covering of SCM heaps with an impermeable sheet is the best option to reduce storage N losses **(Chapters 3 and 4)**.

In addition, because of N conservation and slow mineralisation of the organically bound N during the covered storage, mineral N content of SCM increased at the end of the storage phase. This, together with high mineralisation activities after field application of covered SCM, led to greater crop ANR and DM yield especially when compared to composted SCM, both in the year of application and in the subsequent year. When N losses during storage was taken into account to arrive at the crop ANR of the collected manure from the barn, it turned out that the ANR value was about three times larger in case of covered storage compared to composting of SCM, both for grassland (21 vs. 7%; **Chapter 4**) and arable land (37 vs. 13%, **Chapter 3**). Interestingly, despite of some N losses during covered storage (~10% of the initial N), crop ANR and DM yield were significantly larger from covered than fresh SCM taken directly from the barn, again in both situations.

Irrigation immediately after SCM spreading and use of lava meal as an additive significantly (i) reduced NH_3 emission and (ii) improved crop ANR as well as DM yield **(Chapters 3 and 5)**. Irrigation at a level of 5 mm immediately after surface application of fresh and covered SCM to grassland reduced NH_3 emission by 30 and 65%, respectively, whereas it was not effective in case of composted SCM, likely because of its greater DM content. Addition of lava meal before application at a rate of 80 g per kg of covered SCM resulted in an emission reduction of 46%. By combining it with 10 mm irrigation, an almost 100% reduction in NH_3 emissions from covered SCM was realised, whereas herbage ANR increased from 18 to 26% of the applied N over a growing period of five months **(Chapter 5)**. Incorporation of SCM just before sowing of maize resulted in an ANR value of 39% from covered SCM, whereas this fraction was 20, 29 and 31% in case of composted, stockpiled and roofed manure, respectively **(Chapter 3)**.

Overall conclusions

- The ANR from applied manure in harvested herbage depends on manure type and soil type, and varies widely. It is lower from SCM than from cattle slurry
- Total N losses during storage of SCM can be reduced remarkably by covering the heap with an impermeable sheet. Covering reduced two N loss pathways: (i) gaseous N emissions to air, and (ii) N leaching to surface

waters and groundwater. Field application of SCM that was covered by a sheet during storage, decomposed faster and more N was available for plant uptake, both in the year of application and the subsequent year, when compared to SCM that was stored in traditional ways

- Emission of NH_3 following land application of SCM can be reduced greatly by irrigation or incorporation immediately after SCM spreading, and using lava meal as an additive. Irrigation appeared to be more effective in reducing NH_3 emission than the addition of lava meal. All these NH_3 emission abatement measures substantially increased crop ANR and DM yield
- Overall, combining covered storage with either direct irrigation following application of SCM to vegetated soil or direct incorporation in the soil following application of SCM to arable land is the best practical option to reduce losses and improve utilisation of N from SCM management systems. Depending on the farm infrastructure, losses may be further reduced by the use of lava meal, preferably as a bedding additive in the barn

Implication for efficient manure management

In many industrialised countries, animal manure is a major source of environmental pollution. In contrast, in most of the developing countries animal manure is considered as a key nutrient source to maintain or improve crop productivity and therefore N losses from manure management are more seen as ‘loss of plant nutrient’ rather than ‘pollution problems’. In either case development of efficient SCM management systems is highly important. Based on the results of this thesis, I propose some key management actions to improve the agro-environmental value of SCM.

- If economically attractive, apply lava meal to straw bedding in the barn (Chapter 5)
- Store the barn-produced SCM under impermeable sheet (Chapters 3 and 4)
- Crop and soil-specific SCM application rates must take into account the potential available N (Chapter 2) and degradability of organic N compounds (Chapter 4)
- Incorporate the SCM from covered storages directly into the soil when applied to arable land (Chapter 3)

- In situations where incorporation is not feasible, like on grassland, spread SCM just before a predicted rainfall event or apply irrigation otherwise (Chapter 5)
- Take into account the expected residual N contribution from earlier manure input when determining the manure application rate (Chapter 4)

Samenvatting

Summary in Dutch

Achtergrond en doelstellingen

De hoeveelheid gedomesticeerd vee is gedurende de laatste decennia gestaag toegenomen, en daarmee ook de hoeveelheid mest die jaarlijks wordt geproduceerd. De uitwerpselen van grazend vee die worden uitgescheiden in weilanden kunnen niet worden gecontroleerd, maar die van gehuisvest vee kunnen verzameld en doelgericht aangewend worden. De verzamelde mest is vaak een mengsel van urine, ontlasting, strooisel en gemorste diervoeders en (drink) water met een variabele samenstelling. Op de meeste moderne boerderijen wordt mest verzameld in lekdichte opslag en aangewend als drijfmest: een mengsel van urine, feces en water. Echter, op een aanzienlijk deel van de boerderijen worden uitwerpselen 'aan de bron' gescheiden in een vloeibare en een vaste fractie. De vaste rundveemest (VRM) is meestal een mengsel van feces en strooisel met een hoeveelheid geabsorbeerde urine. De productie van VRM neemt toe als gevolg van de hernieuwde belangstelling voor op stro gebaseerde huisvestingssystemen die bijdragen aan een betere diergezondheid en dierenwelzijn. Een aanzienlijk verlies van stikstof (N) kan optreden in de keten van VRM-management, vooral tijdens de fasen van opslag en toediening. Deze N-verliezen verontreinigen de lucht, het grondwater en het oppervlaktewater, en verminderen ook de bemestende waarde van VRM. De uitdaging is derhalve om een effectief VRM management systeem te ontwikkelen dat een zo groot mogelijk deel van de uitgescheiden N in het systeem behoudt, en dus de gemiddelde verblijfstijd van N op het bedrijf verhoogt en de N-kringloop in het vee-mest-bodem-gewas continuüm verbetert **(Hoofdstuk 1).** De belangrijkste doelen van het onderzoek voor dit proefschrift waren het vergroten van het inzicht in de factoren die N-verliezen tijdens de opslag en na veldtoediening bepalen, en het ontwikkelen en testen van strategieën voor vermindering van verliezen en verbetering van de N-benutting door gewassen uit VRM. De specifieke doelstellingen waren:

- Het analyseren van de interacties tussen een aantal types dierlijke mest en drie grondsoorten ten aanzien van N-mineralisatie en N-recovery **(hoofdstuk 2)**
- Het bestuderen van de effecten van de opslagomstandigheden op (i) de omvang en routes van koolstof (C) en N-verliezen tijdens de opslag van VRM, en (ii) de schijnbare N-recovery (SNR) en droge stof (DS) opbrengst van het gewas **(hoofdstuk 3)**
- Het onderzoeken van de mestafbraaksnelheden, het N-beschikbaarheidspatroon en de SNR tijdens het jaar van toediening

en het daaropvolgende jaar. Dit werd gemeten na toediening aan het bodemoppervlak van VRM dat was onderworpen aan verschillende opslagomstandigheden **(hoofdstuk 4)**, en

- Het analyseren van het effect van verschillende toedieningswijzen op NH_3 emissie en/of gewas SNR van VRM toegediend op grasland en maïs **(Hoofdstukken 3 en 5)**

Om deze doelstellingen te verwezenlijken werd een kasexperiment **(hoofdstuk 2)** en een aantal veldexperimenten **(hoofdstukken 3 tot 5)** uitgevoerd op de experimentele faciliteiten van Wageningen Universiteit, Nederland. In het kasexperiment werden in een pottenproef de netto N-mineralisatie en gewas SNR van VRM, runderdrijfmest en kippenmest bepaald voor verschillende grondsoorten: veen, zand en klei. In de veldexperimenten werd onderzocht: (i) totale C en N verliezen uit verschillende typen VRM opslag (onafgedekt, gecomposteerd, overdekt en afgedekt), (ii) mestafbraak, N mineralisatie en SNR in grasland na oppervlakkige toediening van verse en opgeslagen VRM, en (iii) de gevolgen van irrigatie en het inwerken in de bodem van VRM na toediening, en het effect van lavameel als toevoegmiddel op NH_3-emissie en/of SNR in grasland of maïs.

Belangrijkste bevindingen van het proefschrift

Resultaten van het kasexperiment toonden aan dat de netto N-mineralisatie en SNR afhankelijk zijn van het type mest en de grondsoort. Voor alle typen mest waren de netto N-mineralisatie en SNR het hoogst op veengrond, welke werd gekenmerkt door het hoogste N-leverend vermogen. De klei- en zandgronden hadden een gelijk N-leverend vermogen, maar de netto N-mineralisatie en SNR waren lager in de kleigrond dan in de zandgrond. Dit werd hoogstwaarschijnlijk veroorzaakt door immobilisatie en fixatie van ammonium-N door kleideeltjes. Op elke grondsoort was de SNR lager voor VRM dan voor runderdrijfmest en pluimveemest **(Hoofdstuk 2).** De N-recovery was laag wanneer VRM was opgeslagen op een traditionele wijze (onafgedekt of gecomposteerd) door (i) verlies van N uit de initieel aanwezige anorganische N en uit makkelijk afbreekbare organische verbindingen, en (ii) omzetting van een deel van de resterende N tot stabielere vormen dan oorspronkelijk aanwezig vóór opslag. Tot 31% van de aanvankelijk aanwezige N in onafgedekt opgeslagen VRM en 46% van N in gecomposteerde VRM ging verloren gedurende een periode van ongeveer vier maanden. Overdekte en afgedekte opslag van VRM verminderde de verliezen tot respectievelijk 6 en 12%. Van de totale stikstofverliezen voor elke opslagmethode kon slechts ongeveer een kwart worden toegeschreven aan NH_3-N en N_2O-N vervluchtiging en/of N uitspoeling. De rest kon niet worden verantwoord en ging naar alle waarschijnlijkheid verloren in de vorm van het onschadelijke N_2 gas. Van de totale gemeten stikstofverliezen als gas en in opgeloste vorm leverde N uitspoeling de grootste bijdrage. In vergelijking met de opslag of de compostering in de open lucht werden de verliezen door N-uitspoeling tot een derde verminderd door bescherming van de VRM opslag tegen neerslag, hetzij door overdekken of afdekken. Hoewel overdekte opslag van VRM de totale verliezen van N significant verminderden, waren de NH3 en N2O emissies aanzienlijk hoger dan bij open opslag. Compostering van VRM leidde tot hogere gasvormige N emissies en meer N uitspoeling ten opzichte van de andere opslagmethoden. In het licht van deze bevindingen concludeer ik dat het afdekken van VRM met een ondoordringbare laag de beste optie is om N verliezen tijdens opslag **(hoofdstukken 3 en 4)** te verminderen.

Bij afgedekte opslag werd N in de hoop behouden en mineraliseerde organisch gebonden N langzaam waardoor het gehalte aan anorganische N aan het einde van de opslagperiode toenam. Dit gecombineerd met een hoge mineralisatiesnelheid na toediening van afgedekte VRM, leidde tot een hogere gewas SNR en droge-stofopbrengst vooral in vergelijking met gecomposteerde VRM, zowel in het jaar van toediening als in het daaropvolgende jaar. Wanneer N verliezen tijdens de opslag werden meegerekend bij het bepalen van de SNR van de mest verzameld in de stal, bleek dat de SNR ongeveer drie keer zo hoog was bij afgedekte opslag dan bij composteren van VRM, bij toediening op zowel grasland (21 vs. 7%, **Hoofdstuk 4**) als bouwland (37 vs. 13%, **Hoofdstuk 3**). Het was opvallend dat ondanks enige N verliezen tijdens de afgedekte opslag (~ 10% van de initiële N), de gewas SNR en DS-opbrengst significant hoger waren dan bij verse VRM die rechtstreeks vanuit de stal werd toegediend.

Irrigatie onmiddellijk na toediening van VRM en het gebruik van lava-meel als additief (i) verlaagde de NH_3-emissie en (ii) verbeterde de SNR en de droge-stofopbrengst **(Hoofdstukken 3 en 5)**. Een hoeveelheid van 5 mm irrigatie onmiddellijk na het oppervlakkig toedienen van open en afgedekt opgeslagen VRM verlaagde NH_3-emissie met 30 en 65% respectievelijk, terwijl dit niet effectief was bij gecomposteerde VRM, waarschijnlijk door het hogere droge-stofgehalte. Toevoeging van lava-meel vóór het toedienen van open en afgedekt opgeslagen VRM in een hoeveelheid van 80 g per kg VRM resulteerde in een emissiereductie van 46%. In combinatie met 10 mm irrigatie werd een vermindering van bijna 100% van de NH_3-emissie uit afgedekte VRM gerealiseerd, terwijl de SNR steeg van 18 tot 26% van de toegepaste N gedurende een groeiperiode van vijf maanden **(Hoofdstuk 5).** Het inwerken van VRM vlak voor het zaaien van maïs resulteerde in een ANR waarde van 39% van de afgedekte VRM, terwijl deze fractie 20, 29 en 31% was in het geval van gecomposteerde, open en overdekte mestopslag, respectievelijk **(Hoofdstuk 3).**

Algemene conclusies

- De SNR van de toegediende mest in het geoogste gewas hangt af van mest-type en bodemtype, en varieert sterk. Het is lager voor VRM dan voor runderdrijfmest
- Totale N verliezen tijdens de opslag van VRM kunnen aanzienlijk worden verminderd door de hoop af te dekken met een ondoordringbare laag folie. De N verliezen verminderde via twee routes: (i) gasvormige N-emissie naar de lucht, en (ii) N uitspoeling naar het oppervlaktewater en grondwater. Toepassing op het gewas van VRM die tijdens de opslag was afgedekt met een luchtdichte folie, werd sneller afgebroken en bevatte meer N voor gewasopname, zowel in het jaar van toediening als in het volgende jaar in vergelijking met VRM dat was opgeslagen volgens traditionele methoden
- Emissie van NH_3 na toediening van VRM kan sterk worden verminderd door onmiddellijk irrigeren of inwerken, en door gebruik van lava-meel als additief. Irrigatie bleek effectiever voor het verminderen van de NH_3 emissie dan de toevoeging van lava-meel. Alle deze NH_3 verlies-reducerende maatregelen resulteerden in aanzienlijk toegenomen gewas SNR en droge-stofopbrengst
- Over het geheel genomen was het combineren van afgedekte opslag met hetzij directe irrigatie na toediening van VRM op grasland, of direct inwerken na het toediening van VRM op bouwland de beste praktische optie om de verliezen te verminderen en de benutting van N uit VRM in management systemen te verbeteren. Afhankelijk van de beschikbare infrastructuur kunnen verliezen verder worden verminderd door het gebruik van lava-meel, bij voorkeur als een toevoegmiddel voor het strooisel in de stal

Implicatie voor een efficiënt beheer van mest

In veel geïndustrialiseerde landen is dierlijke mest een belangrijke bron van milieuvervuiling. In de meeste ontwikkelingslanden, daarentegen, wordt dierlijke mest beschouwd als een belangrijke bron voor het behoud of verbetering van bodemvruchtbaarheid en gewasproductie, en N-verliezen uit mest worden dus meer gezien als 'het verlies van plantenvoeding' dan 'een probleem van vervuiling'. In beide gevallen is de ontwikkeling van efficiënte VRM management systemen zeer belangrijk. Op basis van de resultaten van dit proefschrift stel ik een aantal belangrijke beheersmaatregelen voor om de agro-ecologische waarde van VRM te verbeteren.

- Als het economisch aantrekkelijk is kan lava-meel worden toegevoegd aan het stro in de stal (Hoofdstuk 5)
- Bewaar de geproduceerde VRM die in de stal wordt geproduceerd onder ondoordringbare folie (Hoofdstukken 3 en 4)
- Gewas en de bodem-specifieke hoeveelheden toegediende VRM moeten afgestemd worden op het potentieel bodem-beschikbare N (Hoofdstuk 2) en de afbraak van organische N-verbindingen (Hoofdstuk 4)
- Werk VRM uit afgedekte opslag direct in na toediening op bouwland (hoofdstuk 3)
- In situaties waar inwerken niet mogelijk is, zoals op grasland, dient VRM toegediend worden vlak voor voorspelde regen of voordat er wordt geïrrigeerd. (hoofdstuk 5)
- Houd rekening met de verwachte nalevering van N uit eerder toegediende mest bij het vaststellen van de dosering van de bemesting (Hoofdstuk 4)

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Ghulam Mustafa Shah
Wageningen University, April 2013.

Curriculum Vitae

Ghulam Mustafa Shah was born on 4th January 1985 in Jhang, Pakistan. After completing higher secondary school education in 2002, he started to study at University of Agriculture, Faisalabad (Pakistan), where he obtained his 4-year B.Sc. (Hons.) agriculture diploma in 2006 with specialization in Agronomy. He continued his study in the same University for his Masters and completed the course work. In early 2007, he was awarded an "Overseas MS leading to PhD scholarship from the higher education commission (HEC) of Pakistan in collaboration with the Netherlands organisation for international cooperation in higher education (NUFFIC). A few months later he came to Netherlands where he joined MS equivalent research programme at Wageningen University and studied the interaction between manure and soil types on N mineralisation and plant N recovery. In August 2008 he got admission in PhD, under the supervision of Dr. Egbert Lantinga, Dr. Jeroen Groot and Prof. dr. Oene Oenema, at Wageningen University. The main target of his doctoral research was to increase understanding of the factors controlling N losses during storage and after field application, and to develop and test strategies to decrease these losses and improve N utilisation from solid cattle manure management system. This research resulted into outcome of this thesis.

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Refereed scientific papers:

- **Shah G.M.,** Shah G.A., Groot J.C.J., Oenema O. and Lantinga E.A. 2012. Irrigation and lava meal use reduce ammonia emission and improve N utilization when solid cattle manure is applied to grassland. Agriculture Ecosystems and Environment 160: 59-65
- **Shah G.M.,** Rashid M.I., Shah G.A., Groot J.C.J. and Lantinga E.A. 2012. Nitrogen mineralization and recovery by ryegrass from animal manures when applied to various soil types. Plant and Soil (online first) DOI 10.1007/s11104-012-1347-8
- **Shah G.M.,** Groot J.C.J., Oenema O. and Lantinga E.A. 2012. Covered storage reduces losses and improves crop utilisation of nitrogen from solid cattle manure. Nutrrient Cycling in Agroecosystems 94: 299-312
- Raza M.A.S., Saleem M.F., **Shah G.M.,** Jamil M. and Khan I.H. 2013. Potassium applied under drought improves physiological and nutrient uptake performances of wheat (Triticum aestivum L.). (accepted) Journal of Soil Science and Plant Nutrition
- **Shah G.M.,** Shah G.A., Groot J.C.J., Oenema O. and Lantinga E.A. Magnitude and routes of C and N losses from solid cattle manure subjected to various storage conditions. (submitted)
- Shah G.A., Groot J.C.J., **Shah G.M.,** Oenema O. and Lantinga E.A. Simulation of long-term carbon and nitrogen dynamics in grassland-based dairy farming systems to evaluate mitigation strategies for emissions from compensatory loss pathways. (submitted)
- Shah G.A., **Shah G.M.,** Groot J.C.J., Koerkamp P.W.G.G. and Lantinga E.A. Effects of bedding additives on carbon and nitrogen losses from a sloping-floor cattle housing system. (submitted)
- Raza M.A.S., Saleem M.F., **Shah G.M.** and Khan I.H. Effect of Foliar applied Glycinebetaine on growth and physiology of wheat (Triticum aestivum L.). (submitted)
- Shah G.A., **Shah G.M.,** Groot J.C.J., Koerkamp P.W.G. and Lantinga E.A. Bedding additives reduce nitrogen losses and improve fertilizer value of solid cattle manure. (submitted)
- **Shah G.M.,** Shah G.A., Groot, J.C.J., Koerkamp P.W.G. and Lantinga E.A. Nitrogen recovery and dry matter production of silage maize as affected by the application of cattle straw manure amended with various bedding additives. (in preparation)

Conference proceedings:

- **Shah G.M.,** Shah G.A. and Lantinga E.A. 2010. Management strategies to reduce nitrogen losses from solid cattle manure. In: Cordovil C., Ferreira L. (Eds.) Proceedings of the 14th Ramiran International Conference, 13-15 Sept. 2010, Lisboa, Portugal, pp. 204-207
- **Shah G.M.** and Lantinga E.A. 2012. Effects of storage method on N disappearance and herbage N recovery from solid cattle manure. In: Richards K.G., Fenton O., Watson C.J. (Eds) Proceedings of the 17th Nitrogen Workshop-Innovations for sustainable use of nitrogen resources. 26-29 June 2012, Wexford, Ireland, pp. 92-93
- **Shah G.M.** and Lantinga E.A. 2012. First-year's and residual herbage N recovery from fresh and composted solid cattle manures. In: Richards K.G., Fenton O., Watson C.J. (Eds) Proceedings of the 17th Nitrogen Workshop-Innovations for sustainable use of nitrogen resources. 26-29 June 2012, Wexford, Ireland, pp. 110-111
- Shah G.A., **Shah G.M.,** Groot J.C.J. and Lantinga. E.A. 2012. Effects of bedding additives on N losses during storage of cattle straw manure and maize N recovery after field application. In: Proceedings of the international conference on global assessment for organic resources and waste management. 12-15 June 2012, Rennes, France
- Shah G.A., **Shah G.M.,** Rashid MI, Groot J.C.J., Groot Koerkamp P.W.G. and Lantinga E.A. 2012. Effects of bedding additives on nitrogen losses during storage of cattle straw manure and maize nitrogen recovery after field application. In: Proceedings of the international symposium on Emissions of Gas and Dust from Livestock. 10-13 June, Saint-Malo, France

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (5.2 ECTS)

- Alternative strategies to mitigate N loss from solid cattle manure management systems (2009-2010)

Writing of project proposal (4.5 ECTS)

- Strategies to improve N utilisation from cattle straw manure on grassland (2009)

Post-graduate courses (4.9 ECTS)

- Linear models; PE&RC (2010)
- Imaging science; PE&RC (2011)
- HACCP-the basics for the organic sector; Campden and Chorleywood food research association group, UK (2008)
- Global assessment for organic resources and waste management; INRA, France (2012)

Invited review of (unpublished) journal manuscript (1 ECTS)

- Journal of Soil Science and Environmental Management: phosphorus mineralisation and agronomic potential of PPB enhanced cattle manure (2012)

Deficiency, refresh, brush-up courses (3.6 ECTS)

- Soil quality (2007)
- Crop ecology (2008)
- Nutrient management (2008)
- Analysis and redesign of organic farming systems (2008)
- Basic statistics (2009)
- Biological interaction in soil (2009)

Competence strengthening / skills courses (4.2 ECTS)
- Techniques for scientific writing and presenting a paper; WGS (2010)
- How to write a world class paper; WUR-library (2010)
- Information literacy including Endnote; PE&RC (2010)
- Career perspectives; WGS (2012)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.7 ECTS)
- PE&RC Weekend (2008 and 2012)
- PE&RC Days (2009-2012)

Discussion groups / local seminars / other scientific meetings (5.7 ECTS)
- Plant and soil interactions (PhD discussion group) (2010-2012)
- Managing livestock manure for sustainable agriculture (2010)
- Biochar: the soil is the limit (2012)
- WACASA Meetings (2011-2012)
- Nutritional strategies to manage the challenge to today's dairy cow (2009)

International symposia, workshops and conferences (7.3 ECTS)
- 14^{th} RAMIRAN International conference (2010)
- 17^{th} International nitrogen workshop (2012)
- International symposium on emission of gas and dust from livestock (2012)

Lecturing / supervision of practical's /tutorials (1.8 ECTS)
- Organic plant production (2010 and 2011)
- MOA-class (2009-2011)