Recycling of livestock manure in a whole-farm perspective

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Abstract

Intensification increases the environmental impact of livestock production systems. Efforts to recycle nutrients in livestock manure for crop production will effectively reduce several pollution problems, although general solutions are difficult to devise in view of the diversity in production systems, management strategies and legislation between countries and regions. This paper argues that a whole-farm perspective taking side-effects and on-farm interactions into account is needed to determine the cost-effectiveness of strategies to mitigate pollution from livestock manure management. Animal feeding plays a key role in the control of nutrient flows on livestock farms, since the diet affects the composition of excreta. There is a great potential for manipulating manure composition by diet manipulations. Manure is a significant source of heavy metals in soil, and in Europe the permitted levels of Cu and Zn in livestock diets have been lowered to reduce their environmental impact. A variety of environmental technologies are being developed for treatment of manure, many of which have a significant potential for reducing nutrient losses. Internationally agreed and enforced regulations that link pollution control with the adoption of best available technologies could provide the demand that is needed to drive research and development. In the past, policy-makers have typically focused on individual environmental problems. It is essential, however, that the efforts to close nutrient cycles on the farm are accompanied by a corresponding reduction in total inputs, otherwise losses after field application will increase. Integrated assessment tools are needed which can evaluate all internal flows of nutrients, imports and exports, energy use, hygienic risks and contaminants, as well

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as costs, at the farm-scale and beyond. It is important to consider pollution control strategies for a farm in the framework of local and regional pollution control planning. 

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1. Introduction

Globally, intensification of agricultural systems increases the environmental impact of food production. Larger livestock production units result in higher local emissions of pollutants such as odour and ammonia from housing and stores. Larger production units can also lead to higher energy use for transport of livestock manure to be recycled in crop production, and the risk of disease spreading among livestock will increase. Further, high concentrations of livestock increase the risk that nutrients in the manure are used for crop production in excess of crop requirements, which may result in N and P leaching and surface run-off. Negative effects from heavy applications of manure may also include salinisation in semi-arid regions, increases in soil heavy metal concentrations and decreased soil aeration (Bernal et al., 1992, 1993). If livestock intensification continues, there is a need for development of technology and strategies to control the associated environmental problems.

Efforts to close nutrient cycles on farms by recycling of nutrients in livestock manure will effectively reduce several pollution problems, provided hygienic risks are controlled and soil heavy metal limits are not exceeded. However, general solutions are difficult to devise as systems for livestock manure management are extremely diverse. For example, in parts of Europe recycling on the farm effectively reduces the need for mineral fertilisers, whereas in other regions most livestock farms handle the manure as a dilute slurry that is stored in lagoons and frequently applied to spray fields (fields used for disposal of the slurry by irrigation), i.e., with no recycling of nutrients for crop production. Thus, priorities of farmers will be very different and call for different strategies. Pollution control represents a necessary investment for the farmer who wants to maintain a given production level under stricter environmental regulations, or to expand the production without increased environmental impact. The lower production costs associated with intensification make environmental technologies increasingly affordable, but it is important to consider the cost-effectiveness of a given investment. This paper argues that a whole-farm perspective taking side-effects and on-farm interactions into account is needed to determine the cost-effectiveness of mitigation strategies for livestock manure management. Agricultural land (mainly on arable farms) also receives other types of organic waste, such as sewage sludge or municipal composts, but they are not considered here where the focus is on the internal flows of nutrients on livestock farms as influenced by treatment strategies and management.

2. Manure management and emissions

Emissions to air and water bodies are to a certain extent an unavoidable consequence of the recycling of livestock manures within agriculture. Emissions arise from biological, chemical and physical processes associated with the degradation of organic materials during animal digestion, treatment, storage and after land application. Of particular regional and/or global importance are nitrous oxide (N\textsubscript{2}O), methane (CH\textsubscript{4}) and ammonia (NH\textsubscript{3}) emissions to the atmosphere, and nitrate (NO\textsubscript{3}\textsuperscript{-}) leached to watercourses. Agriculture is a major source of the three gases, for which national ceiling targets (NH\textsubscript{3}) or target emission reductions (CH\textsubscript{4} and N\textsubscript{2}O) have been established. Nitrate leaching contributes to eutrophication and may pose a threat to drinking water quality. Of more local concern are emissions of odorous compounds.

Much research has been aimed at quantifying emissions from the various sources within the agricultural production system, and at understanding the key influencing processes (with the associated development of models at a range of scales and complexities) and developing mitigation measures. Research has often been focussed at the source level (e.g., NH\textsubscript{3} emissions from slurry storage) with the aim of establishing emission factors and assessing potential mitigation measures for that source. However, it is important that the whole-farm perspective is borne in mind, and that interactions such as secondary impacts on emissions from other sources and emissions of other pollutants are considered. For example, some mitigation measures aimed at reducing NH\textsubscript{3} emissions from livestock housing and manure storage will result in potentially greater losses at the manure spreading stage, reducing the overall effectiveness of such measures (Weiske et al., 2006), unless measures targeted at manure spreading are also imposed (Webb and Misselbrook, 2004). The potential for increases in N\textsubscript{2}O emissions
the digestibility of zinc in pigs and, to a lesser extent, in poultry.

In ruminants, CH$_4$ production by rumen bacteria contributes significantly to the overall greenhouse gas (GHG) emissions from a farm. Methane is an end-product of the fermentation of carbohydrates in the rumen; it is affected by diet composition and cannot be eliminated completely without adverse effects on ruminant production (Moss et al., 2000). Using modelling techniques, Danfær and Weisbjerg (2006) showed that the CH$_4$ emission (expressed as percentage of gross energy content) decreased with increasing feed intake, decreased with higher proportions of concentrates in the diet, and increased with increasing digestibility of grass silage. Moreover, the CH$_4$ production could be reduced by increasing dietary fat and by increasing starch at the expense of sugar in the diet. The amount of CH$_4$ produced in the hindgut of pigs is much less than in ruminants, but is also affected by the composition of the diet, especially its fibre content.

It is also possible to manipulate diets in order to modify characteristics of faeces and urine specifically to reduce emissions (Dourmad and Jondreville, 2007-this issue). For instance, when the dietary protein supply for pigs is reduced, the NH$_3$ concentration and pH of the manure are decreased, drastically reducing NH$_3$ volatilisation from the building during storage and after spreading of manure (Portejoie et al., 2004). Reductions in pH can also be achieved by reducing the electrolyte balance (Na$^+$ + K$^+$ – Cl$^–$) of the diet, or by adding acidogenic compounds (Guiziou et al., 2006). Moreover, diet manipulation could also be a way to modify odour production. Le (2006) suggested that crude protein and fermentable carbohydrate may play a major role in the production of odour nuisance from pig production.

These different examples indicate that animal feeding plays a key role in the control of nutrient flows on livestock farms. The diet directly affects the amount and composition of manure and resulting emissions. Moreover, the choice of a feeding strategy will also influence the crop rotation of the farm and, consequently, the possibilities for spreading the manure. Hence, diet manipulations have several different effects on the recycling of nutrients in a whole-farm perspective.

4. Contaminants

Contaminants such as heavy metals are present in livestock diets at background concentrations. They may be added to certain feeds as supplementary trace elements for health and welfare reasons, or as growth promoters. A proportion of the metals in livestock manures, as well as those excreted directly onto grazing
land, are recycled through the agricultural system in animal feeds grown and fed on-farm.

Copper (Cu) is added to growing pig diets as a cost-effective method of enhancing performance, and is thought to act as an anti-bacterial agent in the gut. Zinc (Zn) is also used in weaner pig diets for the control of post-weaning scours. Both Zn and Cu are required in trace amounts as poultry enzyme co-factors. Other heavy metals may be present in livestock diets as a result of contamination of mineral supplements (e.g., some limestone added to laying hen feeds may contain relatively high levels of Cd). For all livestock, the majority of heavy metals consumed in feed is excreted in the faeces or urine, and will thus be present in manure that is subsequently applied to land or excreted during grazing. A survey of manures collected from commercial farms in England and Wales in the mid-1990s (Nicholson et al., 1999) found the highest concentrations of Zn and Cu in pig slurry and laying hen manure, reflecting higher levels of dietary supplementation in these livestock types.

Farm manure will also contain heavy metals that have been ingested in drinking water or have been added with bedding materials (e.g., straw). Corrosion of the galvanised metal used to construct livestock housing, and the licking and biting of metal housing components, is a potential source of Zn in some manures. Footbaths containing Cu or Zn may be used as hoof disinfectants for sheep and cattle, and these may be disposed of into manure stores, thus contributing to the heavy metal content of manures spread to land.

Storage and treatment may be considered as potential methods to reduce contaminants in livestock manures. However, conventional storage of solid manures in heaps or by composting will not remove heavy metals. Rather, losses of carbon and nitrogen during storage or composting will concentrate the heavy metals into a smaller volume of material. Thus, stored or composted farm manure can actually contain higher concentrations of heavy metals when spread to land than fresh or untreated manure. Slurry treatment by settlement (in tanks or lagoons) and separation technologies will not remove heavy metals. However, the metals will be associated with particles and relatively depleted in the liquid phase, thus allowing some potential for high-efficiency separation and differential management of the different slurry fractions.

Electroremediation, by which an electric current is passed through a liquid manure and metal ions are precipitated on an electrode, can decrease metal concentrations (Dach and Starmans, 2006). However, at present the technology is unproven at the farm-scale and is unlikely to be cost-effective.

An inventory, constructed to assess the significance and extent of heavy metal inputs to agricultural land in England and Wales from different sources (Nicholson and Chambers, 2006), identified farm manures as the source of approximately 30% of total annual inputs of zinc (Zn) and copper (Cu). The majority of most metals (Ni, Cr, Pb, Cd, As, Hg) applied to agricultural land were from cattle manures, due to the large quantities produced rather than elevated metal contents in the manure. In contrast, smaller quantities of pig and poultry manures were produced, but these supplied 51% of the Zn and 63% of the Cu inputs from livestock manures due to the elevated concentrations in the manure.

Recent legislation (European Commission, 2003a) has reduced the maximum permitted level of Zn and Cu supplementation in livestock diets to minimise their environmental impact. Reductions in Zn and Cu inputs to soils will result as farmers implement this legislation (Table 1), although estimates of manure metal concentrations based solely on feed input do not take into account metals (e.g., Zn) used under veterinary prescription or in spent dip from footbaths containing Zn and Cu that is disposed to manure stores. Further reductions in trace element supplementation need to be based on an objective assessment of the environmental, economic and animal welfare issues related to dietary supplementation compared with the impacts of alternative approaches available for animal production.

Organic contaminants such as persistent organic pollutants (POPs) are generally not considered to be a concern in livestock manures (e.g., Stevens and Jones, 2006).

<table>
<thead>
<tr>
<th>Concentration in diets (ppm)</th>
<th>Cu</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piglets 1</td>
<td>175</td>
<td>70</td>
</tr>
<tr>
<td>Piglets 2</td>
<td>175</td>
<td>70</td>
</tr>
<tr>
<td>Fattening pigs</td>
<td>120</td>
<td>30</td>
</tr>
<tr>
<td>Sows</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Balance (0–110 kg body weight)</td>
<td>119</td>
<td>284</td>
</tr>
<tr>
<td>Intake (g/pig)</td>
<td>42.6</td>
<td>84.1</td>
</tr>
<tr>
<td>Excreted (g/pig)</td>
<td>42.5</td>
<td>81.7</td>
</tr>
<tr>
<td>Slurry composition (mg/kg DM)</td>
<td>1119</td>
<td>2542</td>
</tr>
</tbody>
</table>

Table 1 Estimated balances of Zn and Cu with different pig feeding scenarios

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Scenarios A, D and E correspond to the former EU regulation. Scenarios B and F correspond to the actual EU regulation. Scenario C, G correspond to feeding according to requirements (after Dourmad and Jondreville, 2007-this issue).

a Calculated according to Jondreville et al. (2003).
2003; Petersen et al., 2003). However, veterinary medicines are used extensively in livestock production and are present in livestock excreta. Manure management practices designed to reduce the risks from microbial pathogens by ensuring adequate storage and composting are also likely to reduce the concentrations of veterinary medicines in livestock manures, although further work is needed to fully assess their effectiveness across a range of livestock manures applied to soils.

5. Hygiene and pathogen control

Concerns over health risks from manure handling include: (a) direct transfer of zoonotic pathogens to farm staff and neighbours, (b) the cause and spread of disease affecting farm animals, (c) the contamination of water, and (d) the contamination of food crops. Table 2 gives an overview of the epidemiological pathways. The real fears of neighbours can often be the main reason for revising manure management practices. Contamination of water is also a major concern, especially if surface water is used within the local community. Even if, as in most European countries, spreading of manure close to surface water and on frozen soil is prohibited by law, accidental releases of farm wastes to water has resulted in outbreaks of serious illness, including some deaths from disease (Guan and Holley, 2003).

The health impact of manures by transmission via field crops will depend on the extent and method of application. The risk is particularly high if effluents are applied to the foliage of a growing crop where the leaves are consumed; such practices are not recommended even early in the growing season, well ahead of harvest. There is also a small risk to root vegetable crops where the ground is fertilised with manure prior to planting or sowing, but there is little actual evidence to support this concern. In most other cases, where the application of manure does not come into direct contact with the consumable part of the plant, risks can be minimised by following good agricultural practices.

From a whole-farm perspective the recycling loop of manure back into food production should be as short as possible to minimise environmental impact and ensure a high nutrient use efficiency. If manure from livestock is used on the same farm, the epidemiological risk for the animals does not increase. A special situation arises if central storage units for liquid manure are used by several different farmers, for example in connection with centralized biogas plants. Under such conditions the closed loop of the farm no longer exists, and the epidemiological risks are increased by the number of involved farms and animals involved. Therefore, special hygienic precautions must be taken in centralized plants. Such precautions are necessary, because in a world that shifts to larger animal units and longer food transport distances, the risk for spreading of both new and well-known diseases increases. It must be ensured that, when recycling residues of animal origin, the transmission routes of infectious agents are interrupted. The occurrence of BSE (bovine spongiform encephalopathy), where cattle were fed bonemeal derived from infected cattle, is an example of a too short waste loop, where recycling was optimised regarding use of nutrients in livestock manure, but recycling also of the pathogen, a prion, resulted in transmission of the disease.

There are standard operating procedures for selection of crops in crop rotations to avoid transmission of plant diseases. The same can, and must, be developed for manure management to avoid transmission of infectious diseases to animals and humans. Monitoring of herd health and manure management in the framework of a HACCP (Hazard Analysis Critical Control Points) concept could be a key measure. The monitoring must also include microorganisms that do not affect the health of the livestock, but that of humans. If shed into the manure, such pathogens may be transmitted to humans via the environment. This was demonstrated by a VTEC (verotoxin producing Escherichia coli) outbreak in Sweden in 2005 that was caused by surface runoff to a canal from which, several kilometres downstream, water was used for irrigation of lettuce.

In a herd the primary risk of transmitting diseases is between the individual animals, and risks associated
with manure management are secondary. However, once the disease has been treated, manure can be an important source of re-infection if not properly disinfected. The traditional way of reducing exposure to pathogens by incorporation following spreading is not very effective, because the reduction rate for most bacterial pathogens of faecal origin in soil is in fact lower than the reduction rate when manure is left at the soil surface (Popp, 1967; Rüprich, 1994).

The to-farm management of infected material is complicated by the fact that information about the hygienic quality of the material is often low. For safe recycling of manure, material coming to the farm should be treated in a validated process for removal of potential pathogens following recommendations such as the European regulations (EC) No. 208/2006 and (EC) No. 1774/2002. Here, animal by-products, category 3, and manure has to prove a reduction of pathogens corresponding to treatment at 70 °C for 1 h. The requested inactivation by the treatment should correspond to a 5 log_{10} reduction of Salmonella senftenberg Enterococcus faecalis. When identified as a hazard, inactivation corresponding to 3 log_{10} of a thermo-resistant virus, e.g., parvovirus, needs to be proven. If a chemical process is used, a 3 log_{10} inactivation of Ascaris spp. has to be proven also.

Proper treatment that sanitises livestock manure and other residues in a controlled way, both when it is produced on the farm and when imported, would increase the biosecurity in food production, resulting in healthier animals, higher food production and food safety.

6. Treatment strategies

A wide range of treatment systems exist for handling the various types of manure from livestock farming (Burton and Turner, 2003). However, not all of these will achieve a reduction in pollution, although reducing the environmental impact is often the main objective. The mechanisms by which such systems operate can be classified as (a) stabilisation which enables time for the use of manure nutrients in a growing crop, (b) concentration and export, or (c) elimination of an undesirable loss, such as CH_{4} or NH_{3} emission. The incentive to introduce a given system can vary greatly between countries due to different legal requirements about manure nutrient use efficiency.

A manure management system needs to address the principal local environmental risks and any excess of nutrient over the requirements of the local crop production, since often manure disposal will be (either directly or indirectly) to land application. Good strategies enable a targeted application of nutrients that meets, but does not exceed local crop needs. High manure application rates can improve soil fertility and soil physical properties, but organic N is mineralised throughout the season and may increase NO_{3} leaching during autumn and winter. This dilemma can be resolved by using winter cover crops on arable soils, or by manure treatment to reduce the organic N fraction.

For many farms, the first consideration in manure management lies with easier handling and thus avoiding problems of collection and transport. The simple removal of coarse suspended matter, such as bedding straw, by mechanical separation is a practical way of achieving this. The screened liquid can then be more easily pumped with a reduced risk of pipe blockage, and land application can be done in a more controlled way. The solid material removed is often "stackable", with less than 80% water content, and it may represent 10% or more of the raw effluent. However, its removal will not greatly reduce the nutrient load of the raw slurry, most of the active content being soluble or associated with finer particles. None the less, screened solids can be readily composted, producing a reasonably stable product that is easily transported.

If a separation technique is used where the finer particles are removed, most of the insoluble P and organic N in liquid manure (slurry) can be concentrated in the solid fraction (Table 3), facilitating export of P from areas with an excess. An improved utilisation of the nitrogen remaining in the supernatant fraction is possible due to the high proportion as ammoniacal-N and a faster infiltration of the liquid into the soil (Sørensen and Thomsen, 2005).

<table>
<thead>
<tr>
<th>Manure type</th>
<th>Separation equipment</th>
<th>Removal efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DM</td>
<td>TP</td>
</tr>
<tr>
<td>Pig manure</td>
<td>Centrifuge</td>
<td>60.5 62.3 29.3</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>48.3 60.4 18.6</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>62.1 63.6 20.1</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>32.8 65.6 13.1</td>
</tr>
<tr>
<td>Cattle manure</td>
<td>Centrifuge</td>
<td>65.2 82.0 49.1</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>59.0 77.8 31.7</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>55.0 78.7 27.0</td>
</tr>
<tr>
<td>Anaerobically digested</td>
<td>Centrifuge</td>
<td>68.6 91.0 24.2</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>65.1 64.2 31.0</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>59.7 83.3 25.4</td>
</tr>
<tr>
<td></td>
<td>Centrifuge</td>
<td>55.5 52.4 23.7</td>
</tr>
<tr>
<td>Pig manure</td>
<td>Screw press</td>
<td>27.3 7.1 6.6</td>
</tr>
<tr>
<td>Cattle manure</td>
<td>Screw press</td>
<td>29.9 15.4 7.6</td>
</tr>
<tr>
<td></td>
<td>Screw press</td>
<td>13.1 7.9 4.0</td>
</tr>
<tr>
<td>Anaerobically digested</td>
<td>Screw press</td>
<td>18.4 10.3 7.4</td>
</tr>
<tr>
<td></td>
<td>Screw press</td>
<td>23.0 8.7 6.0</td>
</tr>
</tbody>
</table>

Table 3 Removal of dry matter (DM), total phosphorus (TP) and total nitrogen (TN) with different manure types and separation equipment (modified after Møller et al., 2002)
There remains a risk of NH$_3$ loss from the solid fraction of separated slurry, both during storage and after field application (Amon et al., 2006). Hansen et al. (2006) observed a 4.8% loss of total N as N$_2$O during storage of separated solids, and a 1.3% loss of total C as CH$_4$; these emissions were almost eliminated when the solids were covered with an airtight material during storage.

In many circumstances composting offers a simple and readily accessible method of re-working a variety of organic materials into a useful product. For the most successful schemes, the availability of a vegetable-based substrate to give the product structure and an optimal C:N ratio is essential; straw for animal bedding is ideal, and many systems have been developed on using the manure/bedding mix often known as farmyard manure (FYM). Manure sources suitable for composting include collected solid dung, screened solids and settled sludges, although the proportion of the latter which can be used is limited due to its relatively high water content. If the straw (or similar co-substrate) is readily available at low cost, some liquid manure may be included in the mix, although recirculation of the drained liquid may be required. However, NH$_3$ volatilisation from materials with a high initial ammoniacal-N concentration can be difficult to avoid during composting (Petersen et al., 1998).

For liquid manure the most effective way to avoid environmental losses of CH$_4$ is by biological treatment, either anaerobic or aerobic. Anaerobic digestion is often preferred as there is the clear benefit of a useful gas product, but enthusiasm is less for small operations, or where there is already a cheap source of local energy available. For larger farms, such digestion can be linked with generators to produce electricity in schemes that can sometimes be self-financing. Aeration of slurry is generally less attractive due to the costs of running the aerator, which can reach 1 euro per m$^3$ of liquid manure treated. Aerobic treatment is both quicker and more effective than anaerobic digestion for removal of the reactive organic matter, defined by the BOD$_5$ content, which is achievable in five days; the equivalent for anaerobic digesters is often more than 20 days. The generation of heat (rather than releasing the energy as methane gas) can further accelerate the processes degrading the organic substrate, and subsequent settlement is also quicker.

Aeration of slurry differs greatly from anaerobic digestion with respect to N turnover and potential environmental losses. With aerobic treatment, organic N can be concentrated along with other suspended matter in the sedimented sludge or (to a lesser extent) in screened solids. Ammoniacal-N is not easily concentrated; if unwanted, the main option remains conversion to gaseous N$_2$ via sequential nitrification and denitrification. In the French region of Brittany there are more than 200 commercial systems for aerobic treatment of pig slurry to remove organic matter and nitrogen. This process may be accompanied by the production of some N$_2$O, which reduces some of its environmental credibility (Béline et al., 1999). In addition, for poorly operated systems a major fraction can be lost as NH$_3$ depending on aeration rate and temperature (Park et al., 2005). Clarification processes can aid the recycling of manure nitrogen by enabling easier pipeline transfer for targeted irrigation to more distant fields.

If the retention of nitrogen for crop production is especially important (as for organic farming systems), anaerobic digestion may be attractive as it enables some mineralisation of organic-N in the slurry prior to application. Anaerobic digestion, with the potential for addition of other organic residues, represents a potential whole-farm perspective on reducing GHG emissions (Weiske et al., 2006). Direct emissions from manure management are reduced, and emissions of CO$_2$ are saved by substitution of fossil fuels. However, a whole-farm perspective must consider that the digestate has a potentially greater plant N availability due to organic N mineralisation during digestion (and higher total N amounts if additional co-substrates are used), which may lead to greater NH$_3$ and N$_2$O emissions when spread on the farm unless N application rates are adjusted to account for this.

In some countries combustion of solid manure fractions is being considered as a strategy to remove nitrogen and organic matter. Nutrients like P and K are concentrated in the ash, but the plant availability is reduced by the treatment (Rubæk et al., 2006), and all the nitrogen is lost. It is also important to control emissions of NO$_x$ and other pollutants produced by the combustion process.

Environmental technologies and management strategies are needed to control nutrient surpluses and other risks, but the development is impeded by the lack of well-defined market conditions. Economic policies and regulations of manure management present boundary conditions which determine if a given technology is attractive to the farmer. Internationally agreed and enforced regulations that link pollution control with the adoption of best available technologies could provide the demand that is needed to drive research and development.

7. Manure management — a global perspective

In many parts of the world agriculture is characterised by manure management strategies that weaken the
sustainability of livestock production. An increasing number of livestock farms become specialised with insufficient land for efficient use of manure nutrients for crop production, use of manure as feed increases hygienic risks, and ineffective manure handling on small-holdings can lead to excessive losses.

In North America dairy cattle, like pigs, are typically housed, and excreta are collected as liquid slurry. This slurry is often spread to grassland, or to cropped fields without adjusting the use of mineral fertiliser. Often the liquid from the lagoon is even sprinkled onto a spray field. Beef cattle are kept in open feedlot production systems, where the manure produced is a solid mixture of faeces, urine, spilt feed and, in some regions, straw or other bedding material that is composted and used for soil amelioration and as fertiliser (Larney et al., 2006; Miller and Berry, 2005).

Beef feedlots have also emerged in subtropical areas, for example in Southern Mexico. In this climate zone periods with heavy rain can erode excreta from the open feedlots to rivers or lakes. Pig slurry is deliberately discharged to recipient waters without any pre-treatment, whereas solid pig manure (and poultry manure) is used as feed for beef cattle. A part of the solid manure is mixed with plant residues and fermented (silage), but much of the manure is not treated before it is fed to the cattle.

In Asia, liquid manure from specialised pig farms is often treated in anaerobic lagoons and from the lagoons discharged to rivers. A recycling system has developed where the lagoons are often used as fish ponds; the liquid manure and also manure solids are used to fertilise water plants that are eaten by herbivorous fish (Vu et al., 2007-this issue). Solid manure produced by pigs and cattle is scraped off the floor and composted to be used for soil amelioration. Both the discharge of manure to rivers and the use of manure for animal feeding increase hygienic risks.

African agriculture is dominated by small-holder farms, where manure is often a scarce resource and livestock the central means of concentrating nutrients within farming systems. Here, the importance of controlling environmental losses is not associated with pollution problems, but rather with sustainability (Rufino et al., 2007-this issue). Nutrient losses during manure management can be significant, and crop productivity of home fields are to some extent maintained by import of C and nutrients from remote fields and common lands, where the long-term productivity may therefore decline due to this within-farm specialisation.

In much of Europe manure from pig production is mostly managed as slurry, whereas a significant part of cattle manure is managed as a solid. The focus on environmental impact from manure management has contributed to enforce restrictions on field application. Ammonia volatilisation during manure management and application, as well as N leaching from manure stores, are among the environmental problems which are being addressed in EU member states. National emission ceilings for NH3 emissions are set in the NEC directive (Directive 2001/81/EC); storage capacity and timing of application are addressed in the Nitrate directive (Directive 1991/676/EC). The underlying principle is that a sustainable recycling of animal manure to land will reduce the environmental impact of livestock production, contribute plant nutrients to crops, and reduce the need for mineral fertilisers. However, this policy is challenged by the continued specialisation of livestock production units having increasing problems with safe recycling of manure nutrients.

8. Manure management regulation

Agricultural production systems are influenced, among other factors, by regulations as exemplified above. Most of the rules affecting manure management are aimed at reducing emissions to the environment (point and non-point sources). This section extends the discussion of strategies and obstacles for the implementation of manure management regulation with a main focus on the development in Europe; while different approaches are followed in other regions, the general principles (e.g., defining best management practices) are widely accepted.

In the past, policy-makers have typically focused on individual environmental problems. This approach is illustrated by the Nitrates Directive (1991/676/EC) addressing the reduction of the release of nitrates from agricultural activities to surface and ground water. Although the aim is clear, the principle widely accepted and the limits straightforward, the practical implementation of the Directive is still incomplete in several member countries after 15 years (see Table 4). It highlights the limitations of a “command and control” approach, where farmers are asked to introduce limitations to their activity often without a real involvement and understanding of the problems and solutions. The approach has lead farmers to see regulation as an external constraint, and often to try to circumvent it. Moreover, inspections to oversee that expected technologies and practices are applied is often very weak and hampered by the diffuse (in space and time) operations related to manure management. Additionally, improvements in water quality as a result of the implementation of measures often take years before they can be observed.
Recently, lawmakers have considered a more integrated approach to pollution control with the European Directive, 1996/61/EC “Integrated Pollution Prevention and Control” addressing pig and poultry rearing facilities of certain sizes. These facilities must obtain a permit or license from the Environmental Protection Agency. While the first IPPC Directive focused on pollutants leading to deterioration of air and water quality, policy-makers are now aware that it pays off to address air quality issues together with climate change — both in monetary terms and for the environment — and to take the problem of pollution-swapping more seriously. It is essential, for example, that reductions in gaseous and point-source N losses are accompanied by a corresponding reduction in total N application rates (such as those specified in Nitrate Vulnerable Zones), otherwise increased N loss from agricultural soil may exacerbate water pollution problems. These aspects are being considered in the revision of that Directive (launched at the end of 2005).

Among other considerations, licence conditions shall be based on application of the best available techniques (BAT). The use of a specific technique or technology is not prescribed, but rather licensing will take into account the technical characteristics of the installation concerned, its geographical location and the local environment. If necessary, the permit shall include appropriate requirements to ensure protection of soil and ground water, and measures concerning the management of manure generated by the installation (European Commission, 2003b). BAT, therefore, consists of those technologies and practices that might be commonly called “best practice” for environmental protection. The approach is close to the principles of the Environmental Management Systems reported also in some voluntary standards (ISO 14001, EMAS), which emphasise the role of improving the management in order to lower the environmental impact.

Despite some attempts to use an integrated approach in the regulation of livestock production, farmers still have to deal with several sets of rules addressing individual aspects of the agricultural activity and influencing directly or indirectly the manure management operations. Animal welfare and food safety are just two examples of the increasing pressure of regulations on the production system. Moreover, sometimes the requirements of different laws are not in agreement, presenting farmers with difficult choices. Thus, a different and more comprehensive approach is required to face the current challenge of a sustainable agriculture where multifunctionality is the keyword.

The role of agriculture in the reduction of greenhouse gases, in the production of renewable energy, and in carbon sequestration has received increasing attention during the last years and is considered in recent regulation. The Common Agricultural Policy of the European Union links payments to the farmers to respecting environmental legislation (so-called cross-compliance), thus for the first time giving some means to sanctioning violations.

Even though a gap between the development in scientific understanding of the multiple risks of manure management and the take-up of this knowledge by policy-makers still exists, it is now understood that cost-effective solutions can only be found in integrated policies. Therefore, integrated assessment tools and decision support systems are now required which have yet to be developed. The regulation aiming to minimise
the environmental impact of livestock manure becomes one of the many external constraints that farmers — and these assessment tools — have to consider. When dealing with livestock manures in a whole-farm perspective, the evaluation of cross- and side-effects of regulations based on scientific knowledge still poses significant challenges.

9. Whole-farm models

In the previous section it was argued that integrated assessment tools are needed in order to achieve overall optimisation of treatment and management strategies. This section presents examples of models that have been used in research to analyze interactions between different parts of a management chain, or between C and N flows.

Ammonia emissions from livestock productions contribute to soil acidification, threaten N-limited ecosystems, and NH₄⁺-based particles in the air represent a health risk for humans. Hutchings et al. (1996) assessed the effect of different mitigation strategies on total emissions from cattle farms under Danish climatic conditions with a whole-farm NH₃ model. Their model predicted that establishing a roof on a slurry tank to reduce NH₃ emissions during storage could increase total NH₃ emissions, if no precautions were taken to reduce volatilisation from the cattle slurry applied in the field. This was due to higher emissions after field application as a result of a higher slurry dry matter content, which in turn resulted from the exclusion of rainwater during storage that would otherwise dilute the slurry and facilitate infiltration into the soil.

It is well known that emissions of CH₄ and N₂O during manure management are influenced by temperature, organic matter composition, nitrogen content and storage time. A recent model therefore linked C and N turnover in a dynamic prediction of CH₄ and N₂O emissions during handling and use of livestock slurry. The model results indicated that anaerobic digestion, producing CH₄ at the expense of volatile solids, would cause a 90% reduction of CH₄ emissions during the subsequent storage (Sommer et al., 2004). The calculations further showed the importance of storage temperature before and after transfer to an outside store; hence, residence time is also an important aspect of manure management.

Several models have been developed for analysis of internal and external C and N flows on farms, and for evaluating GHG mitigation strategies (Schils et al., 2007-this issue). The advantage of a whole-farm model, where interactions between the different components are accounted for, is that effects of a management change are transferred throughout the production system. Also, the integration of C and N flows can provide a balanced assessment of environmental impact. Schils et al. (2007-this issue) present calculations with four different models which all predict a positive relationship between farm N surplus and total GHG emissions (see Fig. 1), indicating that farm N surplus could provide an indirect estimate of farm GHG emissions. Such models are useful as research tools, as well as for teaching and demonstration purposes, but the authors emphasise that models generally do not

![Fig. 1. Positive relationships between N surplus of dairy farms and total greenhouse gas emissions have been calculated with four different farm level models of C and N flows representing a wide range of European conditions. See Schils et al. (2007-this issue) for additional details.](image-url)
account for environmental effects of outputs from the farm, and that challenges remain with respect to up-scaling.

10. Conclusions

Controlling environmental losses and contaminant spreading from livestock manure management is fundamental to the development of sustainable production systems. Specialisation and intensification of livestock production systems aggravate pollution problems locally, leading to deterioration of air and water quality. If manure nutrient use efficiencies are not improved, the import of nutrients in feeds and fertilisers will remain high, as will the costs and energy needs for production and transportation, and the surpluses lost to the environment.

A whole-farm perspective is necessary to ensure that the solutions adopted are cost-effective. How does the economic consequences of a change in feeding strategy to reduce surplus P compare with manure separation? Are changes in diets better at reducing odour emissions than treatment of the slurry? Is a storage cover more cost-effective than direct injection with respect to reducing NH3 volatilisation? Integrated assessment tools are needed which can evaluate all internal flows of nutrients, imports and exports, energy use, hygienic risks and contaminants, as well as costs, at the farm-scale.

It is important to consider pollution control strategies for a farm in the framework of local and regional pollution control planning. Investments in environmental technology should be made where the impact on air and water quality is most required. Insofar as intensification of livestock production increases pollution within an area, the lower production costs may facilitate the concomitant implementation of environmental technologies, although Government intervention (e.g., subsidies to encourage change or stricter regulations) may be required.

References


