Soil Use and Management (2005) 21, 141-151 DOI: 10.1079/SUM2005301

Nutrient management for intensive animal agriculture: policies and practices for sustainability

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Abstract. The intensity of animal production around the world has increased substantially during the last half-century, which has led to large problems with the disposal of manures and waste waters. The focus of this paper is on the development of national policies to improve the nutrient management of concentrated animal feeding operations (CAFOs), where nutrients are invariably in surplus. To create proper nutrient management strategies for CAFOs, and to avoid environmental problems when surplus nutrients enter air, soil and water, we need to know the number of animals/birds in the unit, the quantity of manure/slurry produced, how this material is stored and handled and how much land is available for manure spreading. In this paper, we discuss the development of nutrient management strategies for CAFOs in Europe and North America, and the voluntary measures and environmental regulations related to this. For the planning of nutrient management to be comprehensive and efficient, we need expertise from several disciplines. This planning includes development of: animal diets that reduce the amounts of excreted nutrients; efficient storage and land application technologies; land application programmes to optimize yields and reduce nutrient losses; and strategies for use of excess manure outside the farm. Also, large-scale efforts involving many stakeholders (farmers, governments and private industry) are needed to solve problems with nutrient imbalances over the long term. Efforts along these lines include manure relocation, alternative uses of manures, nutrient trading, and a general extensification of animal agriculture. The overall guiding principle for policies and planning should be a balance of nutrients, on farms as well as at larger scales.

Keywords: Concentrated animal feeding operations, environmental regulations, manure, nutrient imbalances, nutrient management

INTRODUCTION

The global nature of animal production has changed markedly in the past half-century, affecting national economies, policies and environment, and altering the social structure of animal-based agriculture. Several trends are apparent. The global animal inventory has steadily increased and appears certain to increase further (Table 1). From 1962 to 2002 there was a 300% increase worldwide in the number of farm animals (FAO 2003). The extent and temporal pattern of this increase, however, varied widely among species, countries, and regions within countries. The largest increase, nearly fourfold in this time period, has been in poultry, followed by a near doubling in the number of pigs, goats and buffaloes, and a 43% increase in cattle. Animal numbers have increased more rapidly in developing than developed countries, particularly poultry (Figure 1). In fact, the stocks of cattle and pigs are now declining in most developed countries, while increasing linearly in developing countries (Figure 1). In contrast, poultry production has increased exponentially in developing countries and in a near-linear manner in developed countries (Figure 1).

The major animal species that present serious environmental challenges for agriculture are usually cattle (beef, dairy), poultry (chickens, ducks, turkeys) and pigs. Trends for the inventory of these species in Canada, the 15 European Union countries (EU-15), and the USA generally parallel the global pattern for developed countries. The greatest increases in animal stocks in all countries during the past 40 years have been for poultry, while the production of cattle has declined in the EU-15 and the USA. Significant increases also occurred in Canada with pigs, with the inventory growing by 44% from 1962 to 2002. Closer examination of these changes also shows that the rate of growth in stocks of cattle and pigs has declined or remained relatively constant in these countries for 1982-2002, relative to the previous 20 years (Table 2).

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Table 1. Forty-year trends in the global livestock inventory (FAO 2003).

	Number of stock (head) x 10^6					Percentage increase [a] 1961-2002
	1962	1972	1982	1992	2002	
Buffaloes	89	110	128	153	167	187
Camels and camelids	19	22	24	24	25	133
Cattle	957	1119	1241	1304	1367	143
Chickens	4041	5546	7760	11 465	15 854	392
Equine	107	113	112	119	110	103
Goats	364	383	480	598	743	204
Pigs	423	669	770	868	941	222
Sheep	997	1036	1129	1158	1034	104
Turkeys, ducks, geese	352	456	663	1061	1562	444
All other	106	160	208	538	529	501
All animals	7453	9615	12 515	17 288	22 332	300

[a] 1962 = 100%.

This decline in stock growth rate also occurred with poultry in the EU-15 but not in Canada and the USA, where poultry production increased more rapidly in 1982-2002 than 1962-1982. As discussed further below, the declining rate of growth in the animal inventory of the EU-15 likely reflects emerging national policies promoting extensification of animal agriculture.

Growth in the global animal inventory quickly translates into a need to manage manures and waste waters. In some settings, managing these materials is simple, and in fact integral, to the ongoing sustainability of agriculture. Many farms in the world effectively use manures as the only source of nutrients for plant growth, either because of the lack of availability of inorganic fertilizers or because of a desire to farm organically. However, in other settings the number of animals present on the farm far exceeds the land base needed to provide feed for the animals, and to recycle the nutrients contained in the manures in an environmentally benign manner. Recent national analyses of the distribution of the animal inventory show a clear trend for geographical concentration of animal production, and for more animals per farm. Animal production has changed from agroecosystems, where the number of animals on a farm was limited by the land to feed them and the labour to sustain their health and productivity, to much larger and more complex operations that often require massive inputs of feed and sophisticated production and marketing infrastructures. This is readily seen for pig farms in Europe, where large operations (>1000 head) are the norm in most countries (Figure 2). Similar trends are well known to have occurred for the swine production industry in Canada and the USA, where farms with hundreds or thousands of pigs are now the norm. In the USA, the average size pig farm in 1997 was 558 pigs and ranged, for the top five pig producing states (IA, NC, MN, IL, IN), from 620 to 3220 pigs per farm. The overall trend for increased size of animal operations, and the geographical nature of this trend in the USA, is illustrated in Figure 3, which shows the change, from 1982 to 1997 by county, in the number of farms with more than 300 animal units of confined livestock.

As the nature of modern animal production has changed, social, political, ethical and environmental questions have been raised about the long-term sustainability of this intensive, geographically concentrated approach to animal production.

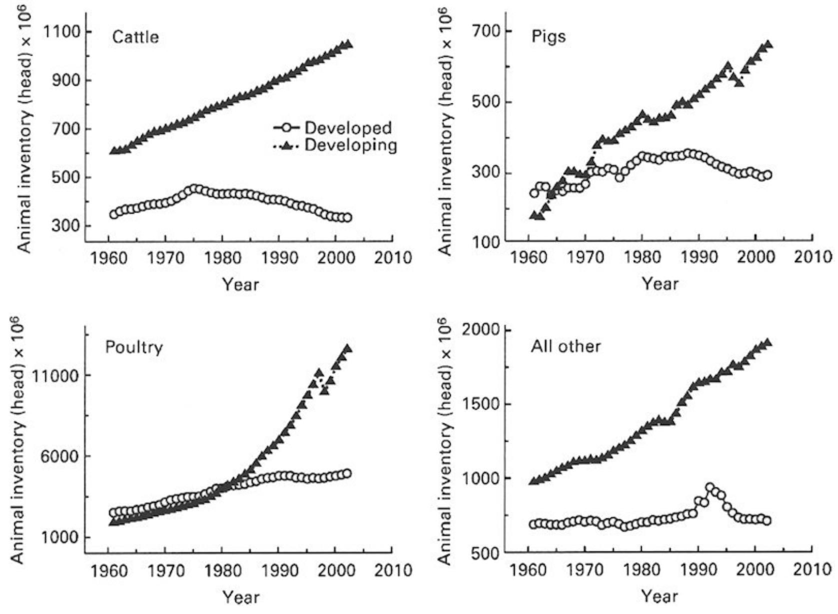

Figure 1. Comparison of 40-year trends in animal inventory/production for developing versus developed countries for cattle, pigs, poultry and all other animals.

Table 2. Forty-year trends for the cattle, pigs, and poultry inventory in Canada, the USA and 15 European countries (FAO 2003).

	Number of stock (head) x 10^6					Percentage increase	Percentage increase
	1962	1972	1982	1992	2002	1962 - 1982 [a]	1982 - 2002 [b]
Canada							
Cattle	11	12	12	12	14	111	113
Pigs	5	7	10	11	14	195	144
Poultry	69	96	98	114	167	143	171
European Union - 15 [c]							
Cattle	87	90	97	87	81	111	83
Pigs	73	95	114	115	124	155	108
Poultry	697	867	985	1016	1138	141	116
USA							
Cattle	100	118	115	98	97	115	84
Pigs	62	62	59	58	59	95	101
Poultry	816	977	1129	1536	2035	138	180

[a] 1962 = 100% [b] 1982 = 100%. [c] Austria, Belgium, Denmark, Ellas (Greece), Espana (Spain), Finland, France, Germany, Ireland, Italy, Norway, Portugal, Sweden, Switzerland, Netherlands, United Kingdom.

As described by Bergström *et al.* (2005) a sustainable agricultural production system would not only meet production goals, but also would ensure that environmental quality is maintained or improved and that the social expectations of the community at large are achieved. Our objective in this paper is to discuss the evolution and future of sustainable nutrient management practices and policies for animal-based agriculture. We focus on animal production systems in Europe and North America, where manure nutrients are regularly in surplus relative to the agricultural land-base available and the impacts of these nutrients on air, soil, and water quality and ecosystem or human health are significant socio-political concerns. In the USA these types of farms are referred to as animal feeding operations (AFOs) or concentrated animal feeding operations (CAFOs, >1000 animal units). In 1997, the United States Environmental Protection Agency (USEPA) estimated that there were 12,660 CAFOs in the USA, accounting for 49% of all the manure N and P generated nationally. Some CAFOs have little or no cropland available to produce crops for feed or beneficially recycle manures and waste waters generated by the animals (sometimes referred to as 'industrial' animal production). Others are actively involved in arable or grassland cropping but lack sufficient land to efficiently use manures and waste waters generated on the farm. In some settings, although there may be no CAFOs, large numbers of small to medium AFOs are concentrated within a small geographical area, creating the same social and environmental problems as might occur with a few large CAFOs.

NATURE OF THE ENVIRONMENTAL AND NUTRIENT MANAGEMENT PROBLEMS WITH CAFOs/AFOs

Diffuse pollution of air and waters by manure nutrients from CAFOs/AFOs is recognized today as a persistent environmental problem, driven by historical and present actions. While our focus in this paper is on the development of sustainable manure management practices that prevent diffuse nutrient pollution, there are many other concerns associated with manure use and with CAFOs/ AFOs in general. Some of the other environmental issues related to animal manures include: bacterial contamination of ground and surface waters; the fate and ecological impact of trace elements (e.g. As, Cu, Zn), growth hormones and antibiotics contained in manures; and air quality problems caused by gases (e.g. NH_3, NO_3) and dusts originating from land applied manures or animal housing facilities. Societal impacts of

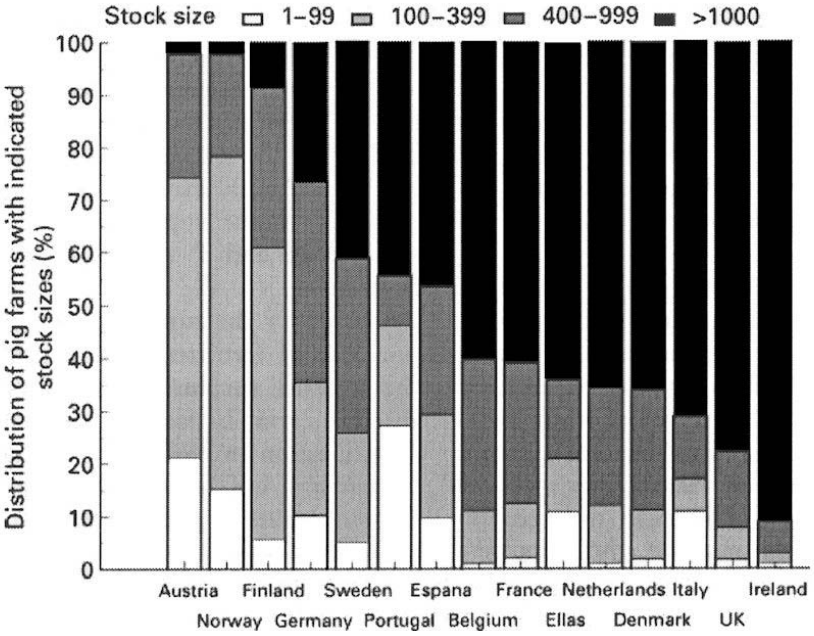

Figure 2. Size distribution of pig farms in 15 European countries in 2000 (Eurostat 2000).

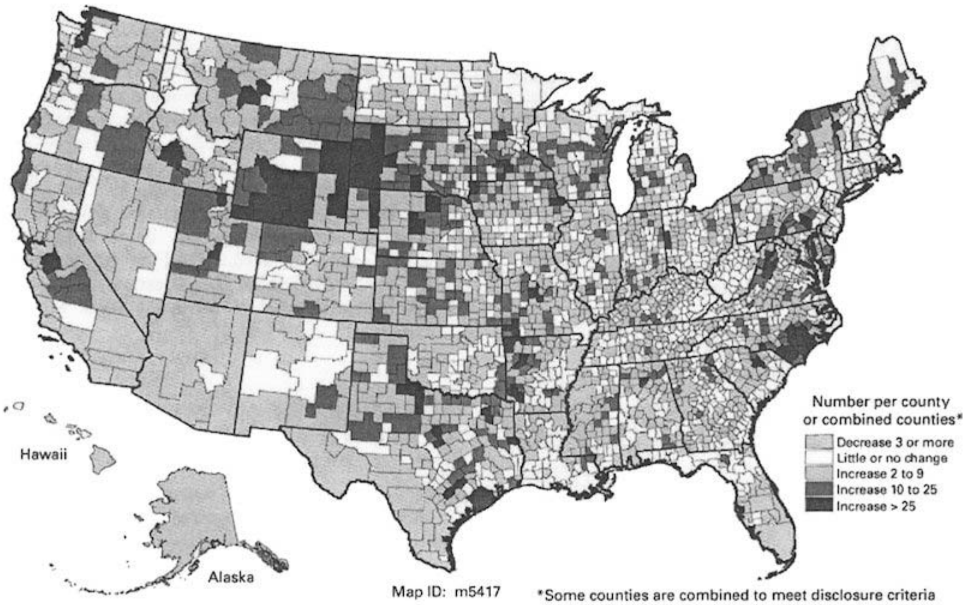

Figure 3. Change in number of livestock operations with more than 300 confined animal units in counties of the USA from 1982 to 1997 (Kellogg *et al.* 2000).

CAFOs/AFOs include: odour problems that create social or legal conflicts between farmers and neighbours; ecological and human health concerns associated with nutrient pollution of ground and surface waters; and animal welfare issues related to the type of confinement practices used. Natural resource issues are involved as well, such as the recognition that most nitrogen (N) and phosphorus (P) inputs to CAFOs/AFOs come from non-renewable sources (e.g. natural gas for N, ore deposits for P). Conserving natural resources is a central tenet of sustainable agriculture and there are growing concerns that intensive, geographically concentrated animal production is an inefficient use of the mineral resources (e.g. phosphate ores) required to produce fertilizers and feed supplements. Thus, the future availability of N and P for food production may suffer. These concerns seem well justified, given the nutrient imbalances commonly associated with such farms, and the fact that Roberts & Stewart (2002) estimated that North America has sufficient P ore reserves to last only 25 years, or perhaps 100 years if higher cost ores can be used.

The nutrient management problems faced by CAFOs/ AFOs depend upon their basic production characteristics, such as the number of animals, the nature of the production facility, the amount of land and type of agricultural systems present on the farm, and the types of waste treatment, handling, storage, and utilization/disposal systems. Despite widespread diversity in these factors, it is apparent that a common, important cause of nutrient management problems is an imbalance between nutrient stocks entering and leaving a farm; or, scaling up, nutrient surpluses in watersheds, regions, or countries. Nutrient balance analyses for many types of production units repeatedly show that N and P accumulate on farms because nutrients in the feed exceed nutrient outputs in animal products and harvested crops. In some cases, the purchase of fertilizer nutrients further exacerbates nutrient imbalances.

De Clercq *et al.* (2002) cited 17 farm-gate balances for dairy farms in the 15 European Union countries (EU-15); utilization efficiency (total outputs from farm over total inputs to farm expressed as a percentage) ranges for N were 18-82% (33%) and for P were 18 - 85% (54%). Three examples are shown in Table 3 and compared with N and P balances for pig farms. These three dairy farms are representative of the EU-15, where 67% of dairy operations have between 20 and 100 cows (average stock size = 24 cows). Despite the fact that these dairy farms are well below the size of what would be considered a CAFO in the USA (700 mature dairy cows; USEPA 2002) all had significant annual surpluses of N and P. Utilization efficiencies for N and P ranged from 19-36% and 39-62%, respectively.

Causes for the surplus varied. In Belgium and the UK, purchase of fertilizers was a major contributing factor to the N and P surpluses, but this was less significant for the Swedish farm. In fact, had fertilizers not been purchased, N utilization would have increased to 65% for the Belgian and UK farms and 46% for the Swedish farm. For P, most inputs to these farms were in the form of concentrates and fodders. Average P utilization for the three farms with or without fertilizer purchases was 52% and 67%. These nutrient balances are similar to those reported by Klausner (1995) for dairy farms in New York (USA) who estimated, for an 85-cow dairy herd, farm-scale

Table 3. Farm gate nitrogen (N) and phosphorus (P) balances (nutrients imported into the farm less nutrients exported from the farm) for selected European dairy and pig farms. (Adapted from De Clercq *et al.* 2002.).

	Dairy farms						Pig farms					
	Belgium[a]		Sweden[b]		UK[c]		Belgium[d]		Denmark[e]		France[f]	
	N	P	N	P	N	P	N	P	N	P	N	P
	(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})		(kg ha^{-1})	
Input												
Mineral fertilizer	228	13	65	1	244	16	0	0	60	1	44	9
Manure	0	0	0	0	0	0	0	0	0	0	0	0
Fodder	67	10	80	17	0	0	0	0	438	95	0	0
Concentrates	162	31	0	0	51	27	32 060	5859	0	0	542	95
Animal products	17	5	0	0	0	0	2970	561	0	0	2	0.4
Atmospheric deposition	40	1	4	0	40	0.2	0	0	28	0	22	0
Symbiotic fixation	0	0	29	0	10	0	0	0	0	0	0	0
Total	514	60	178	18	345	43	35 030	6420	526	96	610	104
Output												
Organic fertilizers	71	12	0	0	0	0	11 960	2945	0	0	116	41
Arable products	7	2	4	1	0	0	0	0	99	16	0	0
Animals and animal products	105	23	48	9	65	17	12 951	2355	147	30	191	49
Other	0.9	0.2	0	0	0	0	308	64	0	0	0	0
Total	184	37	52	10	65	17	25 219	5364	246	46	307	90
Nutrient surplus	330	23	126	8	280	26	9811	1056	280	50	303	14
Utilization (%) [g]	36	62	29	56	19	39	72	84	47	48	50	86

[a] Farm with 26 ha of grassland, no arable crops, and 39 dairy cows. [b] Farm with 48 ha of arable cropland, 41 dairy cows, 15 heifers and 40-60 beef cattle. [c] Farm with 76 ha of grassland, 102 dairy cows and 70 replacement heifers. [d] Farm with no agricultural land and 2000 pigs, with 2.5 production cycles per year. [e] Average of 13 pig farms, averaging 79 ha of fallow and grassland (14%), cereal and other crops (86%), and from 216-387 sows. [f] Farm with 50 ha of arable crops and 220 sows. [g] Utilization = total outputs from farm/total inputs to farm X 100 (%).

farm-scale utilization efficiencies of 37% for N and 32% for P. Most N (75%) and P (65%) inputs were contained in purchased feed. Koelsch & Lesoing (1999) reported N and P utilization efficiencies of 22% for N and 31% for P for a 120-cow dairy farm in Nebraska (USA).

For the pig farms, only one example (Belgium) would be close to a CAFO according to USEPA standards, defined as 2500 swine at 25 kg each (Table 3). Again, all three examples have significant annual N and P surpluses, particularly the Belgian pig farm, which has no arable land or grassland for manure use. Nutrient utilization efficiencies reported for these pig farms were generally higher than for dairy farms. For the Danish pig farms, this can primarily be accounted for by the lower use of fertilizers and a higher percentage of N and P outputs in arable crops (40% and 35%, respectively). For the French farm, reduced fertilizer use and greater export of manure N and P accounted for the higher efficiencies. The Belgian pig farm differed considerably from the other dairy and pig farms and represents a situation where the high efficiency of nutrient utilization was a consequence of the large export of manure N and P from the farm, equal to 47% and 55% of total outputs. This export to nearby arable farms is undertaken to avoid mandatory financial penalties and is an economic cost to pig farmers (De Clercq *et al.* 2002). The fate of the annual 9811 kg N and 1056 kg P surplus on this farm, above and beyond manure export, is unknown. If manure export were not a viable option, N and P utilization efficiencies would decrease to 38%. Similar situations, where favourable nutrient utilization depended upon manure export from farms, were reported for pig farms in Austria and Spain (Cepuder *et al.* 2002; Soler-Rovira *et al.* 2002). In contrast, a Swedish pig farm with 2300 pigs and 73 ha of arable cropland, but no manure export, had lower utilization efficiencies for N (35%) and P (29%) (Steineck *et al.* 2002). De Clercq *et al.* (2002) did not report nutrient mass balances for poultry operations; however, these have been calculated for several scenarios in the USA (Sims 1997; Cabrera & Sims 2000; Beegle *et al.* 2002) and are similar to those for dairy and pigs (Table 4). In general, nutrient surpluses increase and utilization efficiency decreases as poultry operations change from mid-sized farms with arable cropland to large operations where animal production is the sole income source. As with dairy and pigs, most N and P inputs to poultry farms are in feed (N = 70-100%; P = 92-100%).

Catchment, state, regional and national nutrient budgets have also been calculated to quantify better the scale and location of manure nutrient surpluses and to aid in long-range planning efforts. Nord & Lanyon (2003) assessed nutrient transfers in a 740 ha catchment (49% agricultural land) in Pennsylvania (USA). Managed N and P inputs to the catchment averaged 79 and 21 t yr^{-1} mostly as animal feed and manure imported from other catchments. Average managed exports of N and P (44 and 7 t yr^{-1}) were primarily in harvested crops, while 32.3t N yr^{-1} and 0.7t P yr^{-1} were lost from the catchment via stream discharge. Therefore, about 105 kg N ha^{-1} yr^{-1} and 41 kg P ha^{-1} yr^{-1} were apparently stored in catchment soils or, in the case of N, lost to the atmosphere by denitrification or volatilization. Of some note was the fact that only three animal farming operations (pig, dairy, and cash-crop/poultry) accounted for 60% of the agricultural land use and 80% of the nutrient transfer

Table 4. Estimated N and P mass balance for three Delaware poultry (broiler) operations with varying production intensities. (From Beegle *et al.* 2002.).

	Intensity of poultry production [a]					
	Typical		High		Non-crop farming	
	N	P	N	P	N	P
	(t farm^{-1} yr^{-1})		(t farm $^{-1}$ yr^{-1})		(t farm^{-1} yr^{-1})	
Inputs						
Feed	30.6	6.2	61.2	12.4	30.6	6.2
Animals	0.3	<0.1	0.6	<0.1	0.3	<0.1
Fertilizers	4.4	0.5	0.8	0.3	0	0
Biological N fixation	4.5	0	4.5	0	0	0
Total inputs	39.8	6.7	67.1	12.7	30.9	6.2
Outputs						
Animals	13.7	1.7	27.5	3.4	13.7	1.7
Crops	15.1	2	15.1	2	0	0
Total outputs	28.8	3.7	42.6	5.4	13.7	1.7
Nutrient surplus						
Per farm per year	11.0	3.0	24.5	7.3	17.2	4.5
kg ha^{-1} yr^{-1}	109	30	243	72	0	0
% of inputs	28	45	37	57	56	73

Assumptions: 1. A typical Delaware poultry farm has two broiler houses, each with a production capacity of 22,000 birds per flock, and produces 5 flocks per year. The farm has 100 ha of cropland used for the production of corn (35 ha), soybeans (45 ha), and small grains (20 ha). A high-intensity poultry farm has four broiler houses and the same amount of cropland and types of crops. A non-crop farming poultry operation has two broiler houses and no cropland.

2. Feed and animal nutrient inputs and outputs were calculated using standard information on poultry feeds and the composition of young chicks and mature broiler chickens (Sims & Vadas 1997).

3. Fertilizer inputs are based on crop needs at realistic yield goals using the recommendations of the University of Delaware (Sims & Gartley 1996). Note that (i) fertilizer inputs were reduced based on the amount of N and P contained in the broiler litter produced on the farm, and (ii) inputs of fertilizer P were based on soil test P using State-wide soil test P summary information from the University of Delaware, and assuming that starter P fertilizer was used only for the corn.

4. Crop outputs are based on USDA Natural Resources Conservation Services estimates of N and P concentrations in the harvested corn, soybean and wheat grain.

5. Nitrogen surplus includes any ammonia-N volatilized from broiler houses during poultry production and from broiler litters during storage and application to cropland.

in and out of this catchment. Remaining farms in the catchment had no animals, did not use manures, and had N deficits (- 3.2 t farm^{-1} yr^{-1}) and a small P surplus (0.4t farm^{-1} yr^{-1}). Cabrera & Sims (2000) reported that 40 and 56% of the N and P inputs to the poultry-producing region of Delaware were not used and that annual N and P surpluses were 198 and 49 kg ha^{-1} yr^{-1} .

A nutrient balance for the EU-15 estimated soil surface N surpluses of 9.5 and 7.9 million kg N yr^{-1} for 1985 and 1997 (OECD 2001). Manure and fertilizer N accounted for ~31 and 50% of the N inputs in both years. Phosphorus balance data for the EU are not as widely available. However, Ireland recently determined that total P inputs in 1998 were 150 000 t yr^{-1} compared to outputs in milk, meat and harvested crops of 36 556 t yr^{-1}, a national surplus of ~ 14 kg P ha^{-1} yr^{-1} for farmed land (Brogan *et al.* 2001). About 40% of the P input was deposited by grazing animals, 27% was applied to land in organic wastes, and 33% in fertilizers.

A county-by-county analysis of the availability of manure nutrients relative to crop N and P requirements for the USA was prepared by Kellogg *et al.* (2000). Results indicated that recoverable manure nutrients (i.e. the proportion of nutrients in excreted manure that can be collected from confinements after accounting for losses during collection, transfer, storage and treatment) increased by about 20% from 1982 to 1997. Largest increases were with poultry (52%) and swine (35%), and poultry operations had the greatest percentage of recoverable manure nutrients (45% of the N and 38% of the P). About 60 and 65% of recoverable manure N and P were characterized as excess nutrients on farms, that is they exceeded the nutrients taken up and removed in crops and the amount that could be applied to pasture without accumulating nutrients in the soil. In the USA, about 90 000 farms had excesses of P (Figure 4), and 66 000 farms had excesses of N. Farms with poultry accounted for about two-thirds of the farms with excess P, and about half of those with excess N. In all, 73 and 160 counties had excesses of N and P, respectively. Most counties with excess nutrients were dominated by poultry production (82% for N, 64% for P).

The fate of surplus N and P on farms with intensive animal production can be broadly characterized as storage in soils, loss to surface and groundwaters, or transfer to the atmosphere. A voluminous amount of research has been conducted in the past 30 years on the fate, transport and environmental impacts of manure nutrients (Jarvis 1993; Sims & Wolf 1994; Steele 1995; Tunney *et al.* 1997; Hatfield & Stewart 1998; Brouwer *et al.* 1999; Williams *et al.* 1999; Power & Dick 2000; Sharpley 2000).

This research has identified several key problems in manure nutrient management for CAFOs/AFOS; most are not easily resolved, and most are exacerbated as nutrient surpluses increase. The most significant has been long-term over-application of manures to cropland due to the lack of economically viable, off-farm uses for manure. Research has clearly shown that consistently applying manure nutrients in excess of crop needs leads directly to nitrate leaching, ammonia volatilization, and to the accumulation of P in soils to values that are of environmental concern. Another substantial problem faced by farmers managing surplus manure is the logistical difficulty associated with efficiently storing, handling and applying animal wastes. Manures are bulky, heterogeneous materials that are difficult to apply uniformly, and costly to transport even short distances. These factors tend to result in repeated, often non-uniform application of manures to fields closest to the production facility. The timing and method of manure application are often limited by the extent of storage on the farm, the time required to load, haul and apply manures, and soil conditions that limit the use of heavy equipment such as manure spreaders. This can result in manures being applied well in advance of planting, by inefficient methods (e.g. surface broadcasting). It is important to recognize that these problems are

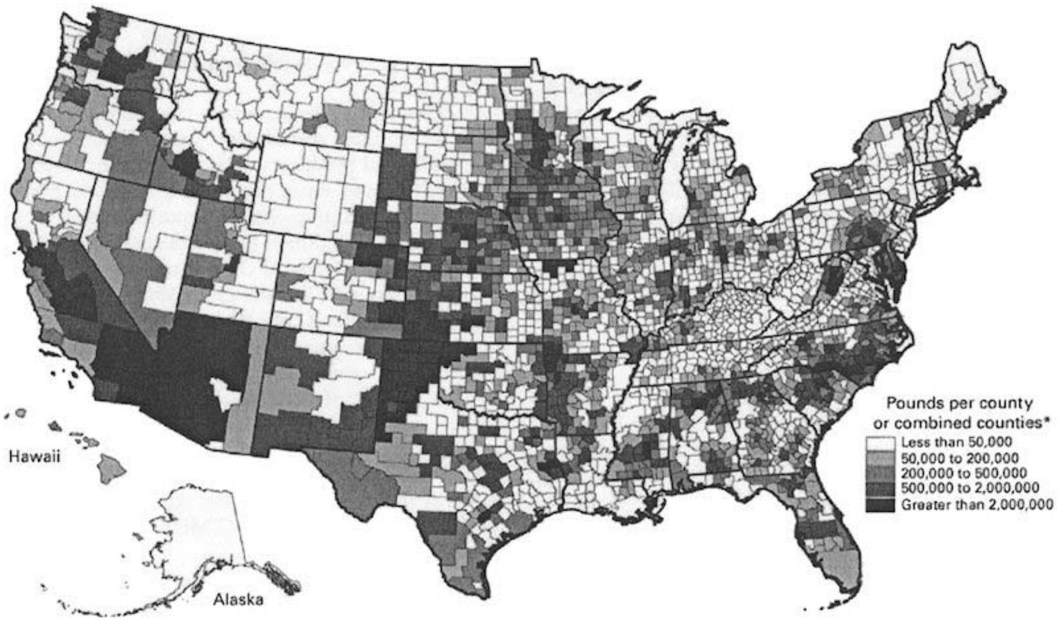

Figure 4. Excess manure phosphorus in counties of the USA, assuming no export of manure from farms (Kellogg *et al.* 2000).

faced by all farmers managing manures, not just those with nutrient surpluses.

EVOLUTION OF NUTRIENT MANAGEMENT STRATEGIES FOR INTENSIVE ANIMAL AGRICULTURE

A variety of strategies has been used to reduce the environmental impacts of intensive animal agriculture. Initially, voluntary actions encouraged by incentives were favoured; more recently, 'command and control' policies that rely more upon regulations have predominated.

Voluntary measures and codes of good agricultural practice

The long-standing approach used for nutrient management on intensive livestock and poultry farms has differed little from other agricultural sectors, focusing on voluntary measures, such as education, technical assistance and financial compensation for adopting 'best management practices' (BMPs). Unfortunately, this approach has not always been well organized, resulting in a somewhat fragmented management effort. That is, while animal nutrition, manure storage and handling, manure and soil testing, manure application, soil and water conservation, and monitoring the success of the overall effort are all integral parts of a BMP system, they have often been evaluated separately in research and disseminated separately by advisory services.

Beginning in the early 1990s, an effort to provide more comprehensive guidance to farmers emerged, as typified by the three UK codes of Good Agricultural Practice that addressed water, soil and air (MAFF 1998). Together the codes provide guidance to farmers and land managers on how to integrate environmental protection measures into decision making (Schoefeld 2002). In brief, the Soil Code is primarily concerned with maintaining soil fertility and preventing soil erosion. The Water Code focuses on ensuring that adequate, but not excessive, N is available for the crop and that nutrient management practices are consistent with all statutory requirements, such as the EU Nitrate Directive. Methods to achieve timely and efficient application of accurate rates of N are detailed, as are practices to avoid, such as spreading N sources on waterlogged or frozen soils or close to watercourses. For P, applications rates are based on soil analysis, crop requirement and consideration of P provided by manures. The Air Code provides guidance on methods to minimize NH_3 losses associated with land application of manures and slurries.

In some EU countries, farmers are rewarded by formal recognition if they voluntarily adopt more intensive nutrient management measures (e.g. Swedish Seal of Quality; Swedish Seal 2001). The MEKA (Market Release and Cultural Landscape Compensation) plan in Germany uses a point-credit matrix that allows farmers to select combinations of BMPs for their farms (e.g. 4 credits for regular soil analyses, 10 points for improved record-keeping, 17 points for adopting organic farming) and receive financial compensation if they adopt the measures for five years (Happe *et al.* 2002). The Environmental Quality Incentives Program (EQIP) of the USDA Natural Resources Conservation Service (NRCS) offers financial and technical assistance to promote BMP adoption. Farmers sign contracts for up to 10 years that provide incentive payments to implement specified conservation practices. For example, in Delaware the NRCS offers a four-tier nutrient management programme. Farmers meeting minimum requirements receive base EQIP funding; while most funding goes to those who use precision soil sampling based on GPS linked to equipment that adjusts nutrient inputs based on soil analyses, soil nitrate testing, split applications of N and yield monitors.

Clearly, widespread adoption of BMPs will reduce the environmental impact of manure nutrients. This approach, however, will not achieve sustainability for farms with manure surpluses, even if all BMPs are implemented. This realization has gradually led to the development of environmental policies that combine incentives and regulations to prevent over-application of manures.

Environmental policy and regulations

European legislative efforts that could in some way restrict manure nutrient application began in the early 1970s, about the same time as the passage of the US Clean Water Act (CWA 1972), and intensified in the 1980s (De Clercq & Sinabell 2002). Key legislation includes: the 1986 Single European Act that gave the EU legal authority in environmental matters; the 1992 Maastricht Treaty that made sustainable growth in environmental matters an EU goal; and the 1996 Amsterdam Treaty that confirmed sustainable development was a goal of European integration. Agenda 2000 (an EU programme with broad social and agri-environmental goals), adopted in 1999, contains regulations that establish rules for payments to farmers in return for environmental actions and also supports sustainable rural development. Farmers are compensated for using BMPs, decreasing livestock density, and conserving areas with high natural value. In 2000, the EU approved the Water Framework Directive that protects inland surface waters, transitional waters, coastal waters and groundwater.

At present in the EU, the main legal measure related to nutrient management is the Nitrate Directive, which mandates designation of nitrate vulnerable zones (NVZs) in each member state. Within an NVZ, mandatory measures limit when and at what rate N can be applied. For example, the maximum amount of manure N that can be applied or deposited by grazing animals in an NVZ is 170 kg ha^{-1} yr^{-1}. Most countries also restrict manure applications based on the time of year (e.g. in the Netherlands manure cannot be applied from 15 September to 1 February. In 2001, about 37% of the total EU land surface was either designated, or scheduled to be designated, as NVZs. Some entire countries are NVZs (e.g. Austria, Denmark, Finland, Germany, Netherlands) while in other countries only some catchments, such as those with intensive livestock or crop production, are NVZs.

At present, only a few EU countries have legislation on or regulations for manure or fertilizer use based on P. Examples are Sweden and Norway, where annual applications of manure P are limited to 22 and 35 kg P ha^{-1}. In the Netherlands, the Mineral Accounting System (MINAS) limits nutrient applications to arable land and grassland based on N and P farm-gate balances for farms with greater than 2.5 livestock units per hectare. From 2003, a financial levy (~ €3 per kg P surplus and €2 per kg N surplus) was placed on N and P surpluses. For all farms, the maximum permissible P surplus is 9 kg P ha^{-1} yr^{-1}. For N, the maximum permissible surplus is 60100 kg ha^{-1} yr^{-1} for arable land and 140-180 kg ha^{-1} yr^{-1} for grassland.

Until the mid-1990s there were few national or state regulations in the USA that directly impacted nutrient management by animal producers. The 1972 Clean Water Act did require CAFOs to obtain permits that mandated practices to prevent point source discharge of nutrients to surface water. However, diffuse pollution from land application of manures and waste waters from AFOs was not regulated, nor were poultry and pig CAFOs, and groundwater impacts were not covered at all by the Clean Water Act (CWA) which strictly addresses surface water quality. Many significant changes in environmental policy that directly affect nutrient management for CAFOs (federal policy) and AFOs (mainly State policies) have occurred in the USA since 1997. At the national level, the most significant changes were the development and now emerging implementation by the United States Environmental Protection Agency (USEPA) of the Total Maximum Daily Load (TMDL) programme and the newly revised CAFO rule.

The USEPA is mandated by law to require that States develop a list of water bodies for which existing point and diffuse pollution control activities are insufficient to attain water quality standards. States are then required to develop TMDLs for pollutants of concern and implement pollution control strategies that restore water quality. A TMDL sets a quantitative limit on the amount of a pollutant that can be discharged daily into a water body. Most TMDL programmes operate at the State level and are the result of lawsuits filed against USEPA by environmental groups for 'failure to perform its mandatory duties under the CWA to identify water quality problems and then improve water quality'. As of 2002, the USEPA had negotiated TMDL agreements with all States for at least one pollutant. Agriculturally derived nutrients are often components of TMDL agreements, and watersheds with large numbers of CAFOs/AFOs now face serious problems in developing the means to reduce diffuse nutrient pollution to levels that meet these new regulatory standards.

The first significant step in the changing US national policy on nutrient management by CAFOs and AFOs was the 1999 USEPA-USDA Unified National Strategy for Animal Feeding Operations. This document defined 'guiding principles' for a joint effort between the nation's lead regulatory agency (USEPA) and lead technical agency for agriculture (USDA) to address the water quality and public health impacts associated with AFOs (USDA & USEPA 1999). Following up on this strategy, in 1999 the NRCS released a national nutrient policy, which requires comprehensive nutrient management plans (CNMP) for farmers receiving technical assistance and cost-sharing funds. In 2001, as mandated by a 1992 federal court decree, the USEPA initiated steps to update regulations associated with the impacts of CAFOs on water quality. The stated reasons for this were that the livestock industry had undergone major changes during the past 20 years, with a trend toward fewer and larger operations (Figure 3). This re-structuring in turn had caused increased discharge of manure nutrients from CAFOs that contributed to pollution of the nation's waterways. The final CAFO rule was promulgated by the USEPA in December of 2002 (USEPA 2002). Key provisions are: (i) land application of manures and waste waters by CAFOs is now a regulated activity; (ii) poultry, swine and cattle CAFOs must obtain permits to operate, which ensure that point source nutrient discharges are prevented; (iii) CAFOs must implement CNMPs that use BMPs to protect water quality; (iv) more stringent requirements for manure storage and record-keeping are mandated.

The USEPA estimated that implementation of the CAFO rule would reduce national discharges of N by 75 000 t, soil erosion by 1000 t and emissions of H_2S and methane by ~ 11-12%. Economic benefits were estimated at more than $200 million per year, from increased use of waters for recreation, decreased nitrate contamination of groundwater, better shellfish harvest, fewer fish kills, reduced costs of treating drinking waters, and less livestock disease. Local environmental policies for CAFOs/AFOs have also changed and in some cases new State laws are more stringent than federal rules (Simpson 1998; Sims 1999).

DEVELOPING NUTRIENT MANAGEMENT FOR INTENSIVE ANIMAL AGRICULTURE

In response to the increase in environmental policies and regulations, those involved in, and impacted by, intensive animal production have pressed for greater efforts to resolve the environmental problems associated with manure nutrients. Inherent in this call for action is the assumption that a sustainable nutrient management plan can be devised for farms intentionally designed to have manure surpluses. While this issue is far from settled, some advances have been made, or are emerging, that may eventually lead to sustainability.

Comprehensive nutrient management planning

Nutrient management planning (NMP) is not a new agricultural activity. Farmers and their advisors have developed and implemented NMPs for decades, and environmental considerations have always played a role in voluntary plans. However, the clear trend to integrate nutrient management into national environmental policies for agriculture suggests that the planning process will be much more formal, even regulatory, in the future. Plans will be required to be comprehensive and encompass all aspects of nutrient generation, use and export from farms. Planners will be better educated and will recognize the need for expertise from many disciplines, such as: animal nutritionists to develop modified diets that reduce the amount of N and P excreted; engineers to provide efficient storage and application technologies; soil and crop scientists and hydrologists to design land application programmes that optimize yields and minimize nutrient loss; and entrepreneurs to provide innovative off-farm uses for excess manure. More record-keeping and monitoring of environmental impacts will be required. Consequently, costs of implementing CNMPs will increase, in some cases partially offset by incentive payments from governments, in other cases borne by farmers and consumers. Wide-scale implementation and documentation of CNMPs will more precisely confirm the magnitude and location of nutrient surpluses in catchments. This should aid regional planners to target the resources needed to implement catchment-scale CNMPs. This is important because individual farmers rarely have the resources to design and construct infrastructure that economically uses nutrient surpluses of the magnitude occurring in some regions. As discussed next, larger scale efforts, involving cooperation between farmers, governments and private industry will be required for long-term resolution of nutrient imbalances.

Manure relocation

The most direct way to resolve manure nutrient surpluses is simply to transport manures to farms where the nutrients are needed for crop production. This decreases the risk of diffuse pollution by reducing the amount of manure that must be stored, handled and applied on the farm, and therefore the potential for nutrient losses directly from storage facilities, from poorly timed applications to cropland, and from heavily manured soils. Because the costs of hauling manure usually preclude long-distance transport, off-farm land application is generally restricted to neighbours (<20 km distant). If a farm is located in an arable area with low animal densities, this can be a viable alternative, particularly if government subsidies defray transport costs. In areas with high animal density, short-distance relocation is less feasible because of the lack of farms with nutrient deficits. Other constraints to manure relocation include odours, disease and pathogen transmission, reluctance of other farmers to bear costs of storing, handling and applying manures as opposed to commercial fertilizers, and economic competition from other generators of organic nutrients (e.g. municipal biosolids, composts). For manure relocation to be successful in the long term, some form of processing that will decrease the weight of material to be transported (e.g. dewatering), minimize odour complaints, and eliminate pathogen/disease concerns will be essential. The unresolved question is whether or not the market for manures will drive processing and promote relocation, or whether this will depend solely upon government subsidy.

Alternative uses

State and federal agencies and the animal production industry have recognized that alternatives to land application of manures must be developed if CAFOs/AFOs with manure nutrient surpluses are to remain viable and if water quality is to improve. A variety of alternatives have been considered, such as composting (Day & Funk 1998; Osei *et al.* 2000), dewatering slurries and using the solids to produce soil substitutes, pelletizing for direct use or inclusion in commercial fertilizers (Gassman & Bouzaher 1995; Hamilton & Sims 1995), and aquaculture (Edwards 1980). Another possibility is to recover manure nutrients in inorganic forms. Recent advances in ultra-microfiltration of organic matter from liquids using polymeric-ceramic membranes enable separation of soluble inorganic nutrients from slurries (Cicek 2003). The inorganic product could then be concentrated by ion exchange, evaporation or reverse osmosis. Growing interest in renewable, ‘green energy’ sources (methane, fuel pellets for electric power plants), may provide incentives to governments concerned about greenhouse gas emissions, and farmers in need of a new economic outlet for manures to expand production of farm-based renewable energy. Such technologies, being widely distributed across the rural landscape, reduce electrical transmission losses, increase grid stability, increase base-load generation capacity (being a 24 h, 7 days a week operation), and complement wind and solar energy that are more intermittent sources. Some American States such as Vermont, Wisconsin and California have implemented laws that foster this idea and farmers have responded quickly by installing anaerobic digestion/co-generation systems. Similar legislation in Germany resulted in several thousand on-farm renewable energy plants.

In the end, sustainable solutions to the management of animal manures must include permanent means to increase their off-farm economic value. Farmers usually respond better to economic incentives than to regulation. Thus, fostering processing and packaging of manures into value-added products (e.g. poultry manure pellets) or expanding use of manures to generate renewable energy and contribute to mitigation of global warming are key options to consider. It remains to be seen whether a combination of private sector investment and government subsidy, driven by new environmental policies, will spur growth and stability in this area and enhance the sustainability of intensive animal production.

Nutrient trading

Nutrient trading means that an increase in nutrient discharge in one sector of a watershed can be offset by nutrient reductions in another. Presumably, the sector desiring to maintain or increase its discharge would subsidise the efforts of the sector that provides the decrease and this trade would be economically beneficial to both. For example, in the Chesapeake Bay watershed (USA), new technologies that reduce N and P discharge to surface waters have been installed in waste-water treatment plants. CAFOs that must continue to apply manure nutrients to arable crops in the watershed, because they cannot relocate manures to other farms or identify alternative uses for their manures, may be a market for these nutrient credits. Many questions remain about nutrient trading. Some are technical, such as the appropriate trading rate between a point source and a diffuse source. That is, how many kilograms of land-applied manure N or P are equivalent to 1 kg discharged directly to water by a point source? Others are socio-political, such as the sustainability of allowing industries with sufficient financial resources to discharge nutrients to the environment indefinitely.

Extensification of animal agriculture

In some areas with extremely high animal densities, animal depopulation has emerged as potentially being necessary to restore the sustainability of animal production. This involves government actions that reduce the number of farms, or number of animals on farms, either through buy-outs or the imposition of such restrictive policies that eventually farmers choose to relocate their operations. For example, in 2001-2002, the Dutch government purchased back animal quota and reduced the number of pigs in the country by 10%, at the cost of about €0.5 billion (10^{12}) (van Staalduinen *et al.* 2002).

FUTURE OF SUSTAINABLE NUTRIENT MANAGEMENT FOR INTENSIVE ANIMAL AGRICULTURE

Despite decades of voluntary effort and increasing national regulation, the sustainability of intensive animal agriculture remains an open question. Nutrient management for such farms is now a complex mixture of comprehensive planning, government subsidization of BMPs, more regulatory limits on land application of manures, and a rather fragmented assortment of government and private sector schemes to provide farmers with options for coping with surplus manure. Is it realistic to expect that these disparate approaches will evolve into a truly sustainable system for an increasingly global industry? Or, will the proven economic sustainability of intensive animal production (more and cheaper animal products) result in public acceptance of some degree of environmental degradation? Will the environmental burden of animal production simply shift from developed to developing countries?

We conclude that a fundamental re-evaluation of national and international nutrient management policies for intensive animal production is needed. The guiding principle for these policies should be nutrient balance, at all spatial scales. Farms producing animals should first and foremost have the land base, or access to sufficient land, to recycle manure nutrients in accordance with codes of good agricultural practice, including those that address environmental protection and natural resource conservation. If not, economically viable alternative uses for surplus manure must be readily available and widely used. Unfortunately, the plain reality today is that nutrient balance will almost always require re-distribution of excess nutrients to farms with an agronomic need for N and P, because of the lack of economically viable, non-agricultural uses for manures. Given this, it is apparent that a truly sustainable system for CAFOs/AFOs ultimately must incorporate the costs of nutrient re-distribution as an accepted component of the economics of food production. Policies, or economic stimuli, are needed to foster this fundamental change if nutrient balance is to be achieved. Without such policies, intensive animal producers will be unable to manage nutrients in a sustainable manner.

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