Renewable Agriculture and Food Systems: 20(3); 127–135 DOI: 10.1079/RAF2004101

Improved manure management and utilization: A systems approach

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Accepted 6 December 2004 **New Concepts and Case Studies**

Abstract

The manure issue is complex and inherently interdisciplinary but, more fundamentally, it requires systems thinking. Current policies, technologies, infrastructure, incentives and modes of thinking about the problem fail to consider the system-wide implications, and thus fail to foster the creation of new and innovative solutions. At the farm level, complexity, uncertainty and lack of compatibility with the current farming system need to be addressed in order to promote better manure management. Production facilities, feed management and waste treatment systems (including centralized treatment plants) need to be designed to allow for beneficial use of manure components. At the industry level, changes in the poultry, swine and beef industries have resulted in concentration, both in terms of decision-making and geography. This currently limits the ability of these farmers to take a systems approach to livestock production. Environmental policies thus need to take account and advantage of this new reality. At the economy-wide level, factors affecting the demand and supply for alternative manure products need to be considered. A number of innovative uses are being developed in the private sector, but there are constraints as far as technology, institutions and infrastructure are concerned. A systems perspective will allow the design of policies and technologies that reduce environmental problems associated with manure, while promoting efficient utilization of the resource.

Key words: livestock industry, manure management, nutrients, systems approach

Introduction

Manure has the potential to be a valuable source of plant nutrients and improved soil tilth, as well as a source of energy and fiber. However, under certain circumstances, manure can also be a source of environmental problems across multiple media. Water-quality problems associated with manure include microbial pathogens, excess nutrients in surface and groundwater, and accumulation of heavy metals. Air quality problems associated with manure are receiving increased attention, and include ammonia, greenhouse gases, particulates and odor, which have effects on multiple geographic scales. Some rural residents are opposed to large livestock operations, due to the air and water quality concerns, as well as the social and economic changes associated with the changing structure of the livestock industry, which has resulted in increasing specialization and geographic concentration. As a result of these and other concerns, the US Environmental Protection Agency (EPA) has issued new federal water-quality regulations for concentrated animal feeding operations (CAFOs) and is considering a new air regulations.

In this article we stress that a systems perspective is key to solving problems caused by manure and making use of the resources contained in manure. The need for a systems approach has been mentioned by Grusenmeyer and Cramer[1] in the context of dairy production and by Hoag and Roka[2] in the context of hog production. Systems thinking recognizes that, particularly for complex problems, it is necessary to understand how components of the system interact with each other, rather than breaking systems down into their components and studying them in isolation[3]. When a broader system-wide view is taken, innovations can be identified which lower costs and improve overall efficiency and system performance. Most current policies, technologies, infrastructure, incentives and modes of thinking about the problem fail to consider system-wide implications and also fail adequately to consider all possible solutions. Systems solutions to manure management problems involve crossing a boundary of some type. One example is the boundary between disciplines. Animal agriculture is inherently interdisciplinary and the need to incorporate environmental and health impacts means that not only do a wider variety of disciplines need to be involved, but that systems thinking is required.

This paper discusses the barriers and opportunities to improving manure management performance by implementing system-wide solutions. The farm is considered the smallest system and is discussed first. Land application of manure as a fertilizer will remain an important use of manure for some time[4]. However, the farm-level decisions are increasingly impacted by industry structure as well as the wider economy. Therefore, the system boundary is subsequently enlarged to include first the industry and, secondly, utilization alternatives that go beyond land application of manure and even agriculture. The final section of the paper discusses policy issues and research implications.

The Farm

While widespread concern and regulations such as the US Clean Water Act are relatively recent, manure management problems are not. An Iowa State University Research Bulletin from 1926[5], before the commonplace use of commercial fertilizers, laments the loss of the fertilizer value of manure, although not yet recognizing the environmental impacts of the wasted nutrients. Despite the extensive research, extension and technical assistance efforts aimed at manure management, adoption of new strategies for land application of manure by farmers has been slow.

Within firms, systems solutions involve combining together multiple internal enterprises that are currently considered separately by the manager. For example, livestock producers would consider the impact of feeds on nutrient content of manure to meet crop fertilizer needs. The decision to consider both enterprises together is not costless. Modified rations may be more costly, the manure and the soils may need to be tested for nutrient content, and additional efforts will be needed to haul and spread manure on appropriate crops located beyond where it was formerly spread. Systems solutions can also involve crossing individual farm boundaries. Manure from one farm can be given, sold or bought by a neighboring farm to be used as a fertilizer, or as an input into production (e.g., mushroom production in the case of broiler litter).

While lack of profitability is important, other factors slow adoption rates. A broader, utility (i.e., well-being) maximization framework, rather than a profit maximization framework, may be appropriate for examining manure issues at the farm level, for several reasons. Utility is a function of the goods and services, both market and non-market, that an individual is able to consume or experience, and is affected by prices as well as his or her income and time constraints. This framework also allows for the disutility of uncertainty and for the full range of factors that affect well-being. Profit maximizing frameworks are not well adapted to issues where risk aversion is important and, as discussed below, uncertainty is a very important aspect of the manure problem. Sociology provides other factors affecting farmer adoption of innovations which could be addressed in a utility framework. Rogers[6] discusses status and discomfort as factors affecting adoption, and it would seem that these would be relevant for the manure problem. Nowak et al.[7] indicate that lower-status employees are usually assigned to manure management activities on the farm. Manure has an unpleasant odor, and also causes a number of health problems in farm workers[8]. In addition, farmer preferences for environmental and social goals are not expressed in a profit maximization framework. Analyzing farmer behavior using a broader framework would enable researchers and policy-makers to predict adoption of strategies and technologies, provide additional levers to affect farmer behavior, and facilitate systems thinking.

One of the reasons that systems thinking is both important and difficult is the complexity inherent in manure issues. In general, complexity increases uncertainty and thus decreases adoption of innovations[6], as well as increasing transaction costs[9]. Manure is a complex environmental problem affecting multiple media, with interactions between the various media. For example, efforts to reduce phosphorus (P) in surface runoff may lead to increased leaching of nitrogen (N) to groundwater, decreased leaching of N to groundwater may increase ammonia emissions to the atmosphere and increased moisture may decrease dust but increase odor. In addition, there are multiple biological and physical processes involved. The nutrient content of manure is a function of growing conditions and plant genetics[10]. Animal use of feed nutrients is affected by level of production, species and genetics[11]. Manure removal, storage and application systems involve biological processes that affect the nutrient content and form of the manure. Once applied to the land, complex soil and plant processes, as well as hydrology and climate, affect the environmental impact of the manure. All these factors increase uncertainty regarding environmental impacts and the fertilizer value of manure.

Systems solutions must reduce or accommodate this uncertainty regarding nutrient content and availability in order to improve the management and utilization of land applied manure. Trialing, or testing out a new innovation on a small scale, is often used by farmers to reduce uncertainty, but this is not an attractive option given time lags and the large investments that are often required for manure management systems. Given the large number of factors affecting the composition of applied manure, quick, convenient and reliable manure nutrient tests would eliminate some of the uncertainty involved with the use of manure as fertilizer[12].

A number of other factors limit the substitution of manure for commercial fertilizers, including nutrient ratios, compatibility with existing systems and transportation costs. A fundamental system-wide problem with manure as a fertilizer is that plant nutrient needs don't correspond with the nutrient ratios in manure, and this is particularly problematic with some species and some types of treatment systems[12]. Another problem is that animal nutrient requirements and the available nutrients in feedstuffs are also not well-aligned[10]. Farmers have to use supplemental phosphorus in swine and poultry diets since P in typical diets has low digestibility for non-ruminants. The amino acid profile in plants is not the same as animal requirements, so to meet requirements of some essential amino acids, farmers overfeed protein. Farmers can reduce excreted P and N (and thus pollution) by improvements in nutrition, such as adding phytase to diets for non-ruminants and providing a better balance of amino acids. However, even dietary changes are impacted by system constraints, such as the number of feed storage bins on a farm.

Understanding the farming system will facilitate the development of strategies and technologies to improve the substitutability of manure for commercial fertilizer, since compatibility with an existing system affects adoption[6]. For example, more emphasis needs to be placed on timing of operations over the year, not just the total hours involved, since the opportunity cost (i.e., the value of time or equipment in an alternative use) may be high at certain times of the year. Applying manure just before planting can reduce nutrient losses, but this could delay planting compared to applying commercial fertilizer. Overcoming issues of convenience and odor would make manure more competitive with commercial fertilizers. Compatibility also relates to equipment that may be needed for manure application.

The market value of manure is also affected by transportation costs, which are determined, in part, by treatment system design. For example, the high water content of manure effluent from liquid handling systems greatly increases transportation costs. Dry broiler litter has lower transportation cost per unit of nutrient and has been shipped greater distances[13] than wetter swine or dairy manures, which have generally lower or even negative economic value.

Intensive rotational grazing is an example of a sustainable agricultural practice that takes a systems approach. In intensive rotational grazing systems, the land resource serves the multiple-uses of food production, food storage, animal housing and waste disposal, thus efficiently using and recycling available resources. Among the many efficiencies gained in intensive rotationally grazed systems, 60–99% of minerals and nutrients are recoverable[14]. Since all these functions occur on the same facility, issues of transaction costs and market infrastructure are minimized. When intensively managed, environmental and economic goals are both enhanced. Given the changing structure of livestock industries, and thus the locus of decision-making, Hinrichs and Welsh[15] indicate that it may be possible to get cow–calf operations and dairy operations to adopt this technique, but that it is less feasible for the poultry and swine industries.

Fundamentally, production facilities and feed management need to be designed to reduce problems and increase utilization opportunities, rather than just focusing on what to do with manure after it comes out of the barn[1,16]. Management specialist Steven Covey[17] says we should begin with the end, in this case manure utilization, in mind. As an example, Total Quality Management has been suggested by Grusenmeyer and Cramer[1] as an appropriate strategy. Alternatively, ISO 14000 is a series of international standards which provide a framework for the development of an environmental management system[18] and which could be applied to animal agriculture. Porter and van der Linde[19] show many cases where environmental regulations have stimulated innovations that actually increase profitability because the firm is forced to overcome organizational inertia and carefully examine their whole production system. In addition, they indicate that regulations often address areas where there are resource inefficiencies and thus potential for technological and process improvements.

The Industry

Farm structure is evolving from many diversified crop–livestock farms to fewer, larger farms that specialize in either crop or livestock production. In addition, livestock producers are becoming more geographically concentrated, located in clusters near processing and infrastructure services[20]. These changes can create an imbalance between nutrients produced by livestock operations and crop needs at the farm and regional levels, which can have negative impacts on the environment[4]. Integrators, firms that contract with farmers to raise livestock while providing the feed and animals, are common. While the industrialization process has resulted in efficiencies due to economies of scale and increased use of technology, it has also produced a number of unintended consequences, including environmental consequences. Contract production means that the responsibility for decisions regarding production of livestock, and thus manure nutrient concentration, is separated from the producer-level decision-making regarding waste management. Traditional diversified farms took more of a systems approach within a local context and cycled nutrients among crop and animal enterprises, but that has been lost with industrialization so new systems and incentives need to be designed.

However, systems solutions may be possible within the food system. In essence, this represents the integration of two or more vertically aligned stages in the marketing system through greater coordination. It can be accomplished through expanded ownership or new market exchange mechanisms (such as contracting). On the input

https://doi.org/10.1079/RAF2004101 Published online by Cambridge University Press

side, the reformulation of feed mixes to reduce water or air emissions has been identified as a promising system innovation. A barrier to adoption may be that the changed feed mix or additive may be at higher costs to the integrator, while the benefit of use accrues in farm-level manure management or beyond the farm in downstream water uses. Some poultry integrators have incurred additional costs of change-over to use these feed additives, and/or required growers to utilize these less polluting types of feeds as part of their contract[21]. In Virginia, public funds have been used to help feed suppliers make the changes needed to convert their feed lines to provide phytase in a form that is usable by growers. Overcoming this bottleneck and conversion cost was critical to more widespread availability to poultry growers in that state (J. Pease, personal communication, 2001).

Viewing manure problems from a systems perspective allows new solutions to be envisioned. Co-permitting (requiring both producers as well as other entities with substantial operational control of CAFOs to obtain a permit) may have potential to introduce a systems approach. While entailing costs to integrators and other food system participants, co-permitting appears to hold promise as a way to reduce transaction costs and facilitate broader, more cost-effective solutions. In other words, co-permitting recognizes that the feed supplier/integrator/processor influences, or has primary control over, many outcomes in vertically coordinated food sectors. This approach has the ability to affect environmental externalities directly by bringing the environmental consequences of decisions to bear on the actors making the decisions. In addition, by working with the decision-making entities at the regional level, a co-permitting approach has the potential to attain regional scope or scale economies needed for cost-effective manure transport, treatment and disposal.

There are many significant unknowns related to co-permitting. For example, one of these unknowns relates to how the benefits and costs of change would be shared. Some fear that co-permitting would allow integrators to further take advantage of growers[22]. Gains from coordination and reduced transaction costs within the poultry meat industry must be weighed against pervasive economic power conflicts between some contract poultry growers and the companies who own the birds and feed[23]. Developing new manure product and service industries separate from the existing production contract relationships may diminish these conflicts. Integrators could play an important role by supporting new infrastructure development, such as grower and third-party manure processing and handling enterprises[24].

Beyond Land Application and Agriculture

A systems approach can suggest possible new ways to reuse and recycle manure into 'green' products by combining existing stages in the manure distribution chain or creating new stages. As discussed below, there is a significant and growing demand for 'green' and renewable products. A least-cost disposal strategy for managing manure emphasizes lowering costs rather than generating revenue. Creating a positive value for manure requires a goal of increasing revenue from all outputs. Investments in capital and labor to create 'green' products may be profitable. These new and alternative technologies will go beyond land-applied uses for manure.

Treatment/conversion technologies convert inputs into outputs and thus determine the supply of usable and surplus manure products. The evaluation of new manure conversion technologies requires understanding both the inputs and the desired outputs. Unfortunately, animal production systems, manure treatment technologies and regulations have not been designed to promote beneficial use. Facilities designed solely to maximize livestock revenue created forms of manure that are difficult to process into valuable outputs. Utilizing a systems approach would enable firms to use technology to capitalize on the geographic concentration of the livestock industry, which is a problem when only land application is considered.

Ultimately, manure is unused corn, soybeans and water. The concept of unused feed allows manure to be viewed more easily as a feedstock into a new technology, since it is the raw manure qualities and characteristics that determine usability. Manure conversion technologies that determine usability can be divided into biological and physical technologies. The biological conversion technologies include anaerobic microbes used in lagoons and methane digesters, aerobic microbes used in composting, and other higher-order organisms. Physical conversion technologies are more sophisticated and often require significant capital investment. These technologies include combustion[25,26], distillation of ethanol from manure[27], conversion of manure to biodiesel[28], heat and pressure for fiberboard and containers[29] and crude-oil equivalents[30], to name a few.

Demand for processed manure

There is a growing demand for organic/biorenewable products[31,32]. Manure products can meet this demand by selecting nontraditional manure processing technologies that transform the manure supply into useable products[33]. For example, anaerobic digesters produce methane gas, but to use the energy the methane must be converted to electricity and distributed consistently to electricity users. The economics of the technology, the demand for the products produced and the overall marketing system determine whether manure stocks will be used or wasted.

Effective use of manure stocks requires identifying the economic uses for the materials. These can be grouped into nutrients, soil amendments, fiber for industrial uses and energy sources. The traditional use for manure is as a substitute for the nitrogen and phosphorus in commercial fertilizers, but it is difficult to compete with the ease-of-use and lower costs of chemical fertilizers, as discussed previously. There was often excess manure when the focus was only on nitrogen, and this situation will be exacerbated by the new regulatory focus on phosphorus, so new uses are increasingly important.

The technical benefits of adding organic matter to soils are well documented, but relatively little is understood about the economic benefits. Manure compost demand is growing in existing markets for landscaping, horticulture nurseries, topsoil, golf courses, Christmas trees and ornamental plants[31]. As these industries grow, the demand for organic amendments will also grow. Ralph Jurgens of New Era Farm Services in California, prepares large volumes of various composts with specific characteristics[34]. Demand is growing for environmental and reclamation uses of compost as well. The EPA has documented the value of quality composts for use in landfill covers, roadbeds, biofilters, erosion control, mine reclamation and wetlands restoration[35].

Manure can also be converted into new forms of nutrients, proteins and carbohydrates, by higher-order organisms, which are in greater demand than the forms found in raw manure. Two examples of these technologies use algae[36,37] and black soldier fly larvae to convert manure to other sources of feed nutrients[38].

The proteins and carbohydrates in manure can be used for industrial processes. Deland Myers[39], at Iowa State University, has developed different fiber boards from manure and bedding. In Connecticut a small firm is commercializing the process of making greenhouse pots out of pressed manure and bedding[40].

The manure energy market is emerging for solid, liquid and gaseous fuels. These markets are in various stages of development but significant distribution and infrastructure challenges remain. Solid manure can be burned directly in power plants or it can be gasified[41]. Furnaces are being developed for both on-farm and centralized off-farm use. Research continues on producing liquid renewable fuels, such as ethanol and biodiesel, from manure, even though it is not the feedstock of choice for either fuel. Anaerobic digestion of manure is the most common source of gaseous energy. Methane digesters continue to be installed, although their economic success has yet to be established[42]. A commercial 'experiment' by ConAgra and Changing World Technologies in Carthage, Missouri has produced a crude-oil equivalent from animal fat and protein[30], although manure could also be used as a substrate. That process has significant potential and produces a range of carbon-based oils and products.

Some firms receive fees for hauling away waste and dead animals, essentially buying inputs at a negative price. Many of the manure-utilization successes are based, in part, on taking someone else's organic residuals, processing it into multiple products, and selling it. For many of these technologies, margins are so small that commercial success will require involvement in multiple, complementary, markets (e.g., waste disposal, an organic soil amendment and energy). Economic success will be enhanced with the development of the market and distribution infrastructures for these products.

Manure market infrastructure

An important factor affecting the implementation of multi-farm systems solutions is the existence of market infrastructure, including intermediaries, such as manure brokers and haulers, that facilitate transactions. Though not well documented, some manure market infrastructures already exist[43]. Manures have been used to grow mushrooms for decades, and across the broiler-growing areas, broiler-house clean-out businesses remove the chicken litter and apply it to neighboring pastures. Some states, such as Pennsylvania, have attempted to enhance this infrastructure through the certification of manure brokers and haulers[44]. Missouri has a new web-based Litter Market Exchange to facilitate communication between buyers, sellers, haulers and spreaders.

The growth of US soybeans shows how, over time, infrastructure development can facilitate exchange and influence economic feasibility. It has taken more than 60 years of distribution-channel development, genetic improvements, energy savings, new processing technologies and new soy uses, to create global markets for oil and protein from soybeans. Building a new commodity marketing/distribution infrastructure for manure products will be costly and time consuming, but appropriate incentives may facilitate this process.

Policy Implications

Desirable policies are cost effective, limit unintended consequences and consider the entire system being regulated. There are four major sources of unintended consequences of social action[45]. Two are particularly relevant to manure issues: (1) uncertainty or insufficient knowledge because of the complex nature of the phenomenon; (2) error due to a lack of thoroughness or a determined refusal to consider all aspects of the problem. The multimedia nature of the manure problem means that focusing on just one component or one medium may exacerbate other problems. For example, regulations based on nitrogen have had the perverse result of providing incentives for poor manure quality as far as meeting crop nutrient needs is concerned, since reducing the nitrogen content by volatilizing it means that manure has to be applied to fewer acres. Those regulations have also promoted the surface application of manure and phosphorus build-up in the soil. An example of the second source of unintended consequences is the tendency for scientists to overlook the human dimensions of the problem.

Missed opportunities?

The EPA published new federal Clean Water Act regulations for CAFOs in February 2003[46]. The first

Table 1. A systems evaluation of the Environment Protection Agency (EPA) concentrated animal feeding operations (CAFO) rule revision.

Proposed CAFO rule element	Use of systems approach	Included in final EPA CAFO rule
Inclusion of dry poultry operations and immature stand-alone enterprises	Yes	Yes
Production and land application require permits	Yes	Yes
Phosphorus in addition to nitrogen management	Yes	Yes
Co-permitting of feed suppliers/integrators	Yes	No
CAFO definition based on animal-specific thresholds (i.e., no longer combining animal units)	No	Yes
Land application area requirements that address manure exported to other farms	Yes	No

significant changes in the rules since 1977, these regulations were a result of a court order in response to a lawsuit by the Natural Resources Defense Council. They claimed that the EPA was not implementing the Act according to schedule, resulting in inadequate protection of the water quality in the nation's rivers, lakes and coastal waters. The EPA also indicated that an important reason the rules needed to be changed was to reflect the fact that the structure of poultry and livestock industries had changed significantly since the 1970s[47,48].

Modification of the EPA CAFO rules involved two steps. In December 2000, a draft proposal offering a menu of options for revising the rules was released. After reviewing public comments on the draft and conducting required analyses, EPA released the final rules in December 2002. One can evaluate elements of the CAFO rules in terms of systems thinking, as shown in Table 1. Of the five proposed elements that incorporated a systems perspective, three—dry poultry and immature animals, land application in addition to production areas, and the inclusion of phosphorus—made it into the final EPA rules. The two that did not make it into the final rules were co-permitting and extending land application requirements to farms where manure was exported. These two elements have the following in common: each involved crossing firm boundaries and would have involved clarifying or changing property rights and costs (either rights or responsibilities) related to nutrients in feed or manure. In addition, the final rule includes an element that contradicts systems thinking; a simplified CAFO definition based on species-specific thresholds, rather than combining animal units across species. For mixed species operations, separating manure by animal species means that the total manure, and the environmental threat potential, could be equivalent to a single-species operation, yet the operation would not be required to have a permit.

In addition, the new regulations did not foster efficiency improvements, feed formulation and genetics as means to reduce environmental impacts. The new regulations do little to provide incentives for alternative uses of manure, and often even hinder potential market solutions. For example, the potential for composted manure is not addressed, even though the EPA itself recognizes the environmental benefits. Treated manure is codified as a waste and liability, and regulations do not connect the permitted facilities to new uses for manure.

The political economy surrounding livestock production and marketing may present a barrier to the successful implementation of systems solutions. If a change is costly to certain groups, and they have significant economic or political power, they will likely block the change. For example, poultry and cattle producers actively opposed proposals at the national level and in Maryland to incorporate co-permitting of integrators that contract with farmers in order to meet the goals of water quality and nutrient management laws[49,50].

More generally, systems solutions are also possible within natural resource boundaries, including watersheds and airsheds, but face a number of obstacles. Natural boundaries rarely coincide with economic, social or political boundaries. Costs and benefits are experienced by different groups. For example, farms located in tributaries of a watershed may be important generators of manure nutrients and contribute to excess nutrient loads downstream, leading to pollution problems and loss of fishing, recreation or others uses and benefits. Greater efforts toward improved manure management would likely increase the costs for upland farms, and since they are unable to capture the environmental benefits of these efforts, given current institutional arrangements, they have little incentive to change practices.

Research is needed on policies and institutions that allow those benefitting from water quality improvements to compensate those that experience added costs. A possible system-wide solution would involve a negotiated or 'market-like exchange', whereby the winners compensate the losers. The EPA is examining the potential for water-quality trading, and recently released a water-quality trading policy[51]. While some success with trading in the air pollution context has occurred, there has been limited success in water-quality issues. Among the barriers encountered have been high transaction costs, lack of, or unclear, property rights[52] and high information costs associated with linking water-quality changes to land uses[53].

There are other positive developments. The USDA-NRCS Environmental Quality Incentives Program (EQIP) provides incentives for systems approaches to improve environmental quality impacts from agriculture. The program now focuses more heavily on animal agriculture than in the past. Cost-sharing is available for intensive rotational grazing systems. In addition, comprehensive nutrient management plans are required for most animal feeding operations in order to receive EQIP funds. Innovative public policies, such as the renewable energy portfolio and the green product procurement programs, are stimulating demand for organic and biorenewable products. These programs, as well as guaranteed loan and grant programs, act as a sort of venture capital to jump-start new industries. Other private-sector efforts, such as the US Composting Council's Seal of Testing Assurance, create a label that assures a minimum quality, similar to regulated feed and fertilizer labels[54].

More policies that reflect systems thinking are needed. At the farm level, EQIP represents a step in the right direction. Policies that increase the substitutability of manure for commercial fertilizer by addressing the existing farm-level constraints need to be developed in light of phosphorus-based regulations. Policies should also recognize the constraints and opportunities presented by structural changes in agriculture. There must also be incentives to create manure solutions, by focusing on both demand and supply issues, rather than just focusing on what to do with manure as an afterthought. In some cases, there is a lack of research-based information on which to base decisions.

Research Implications

Increased knowledge regarding the physical processes related to manure cannot, by itself, overcome the problem of unintended consequences. A commitment to systems thinking and to a process of thorough analysis of manure issues and potential consequences and opportunities is required. At the farm level, agricultural research, extension and technical assistance programs should take into account the full range of constraints faced by farmers if innovations are to be adopted. Technologies that increase the substitutability of manure for commercial fertilizers, by reducing uncertainty and increasing quality and convenience, need to be developed.

Technologies and production systems that improve the suitability of manure for industrial and energy uses should be developed. Some research is already occurring in both the public and private sectors, but new policies could facilitate these efforts. Research on the links between agricultural and environmental policies and the incentives for development of new industries will require a systems perspective. The effect of industry structure, infrastructure and marketing channels on the development of value-added manure industries must be examined. Systems analysis of the existing institutions and property rights that determine incentives at the farm, industry and economy-wide levels is needed.

Concern regarding the effects of animal agriculture on air quality from esthetic, health and global warming perspectives is increasing. Scientific research on air-quality concerns, as well as interactions between air quality and water quality, is needed. Research is also needed to design environmental policies that are appropriate for situations where there are multiple media, multiple pollutants and high levels of uncertainty. Systems, rather than reductionist, thinking is obviously required.

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