SPECIAL SUBMISSIONS

Sustainable Land Application: An Overview

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ABSTRACT

Man has land-applied societal nonhazardous wastes for centuries as a means of disposal and to improve the soil via the recycling of nutrients and the addition of organic matter. Nonhazardous wastes include a vast array of materials, including manures, biosolids, composts, wastewater effluents, food-processing wastes, industrial by-products; these are collectively referred to herein as residuals. Because of economic restraints and environmental concerns about land-filling and incineration, interest in land application continues to grow. A major lesson that has been learned, however, is that the traditional definition of land application that emphasizes applying residuals to land in a manner that protects human and animal health, safeguards soil and water resources, and maintains long-term ecosystem quality is incomplete unless the earning of public trust in the practices is included. This overview provides an introduction to a subset of papers and posters presented at the conference, "Sustainable Land Application," held in Orlando, FL, in January 2004. The USEPA, USDA, and multiple national and state organizations with interest in, and/or responsibilities for, ensuring the sustainability of the practice sponsored the conference. The overriding conference objectives were to highlight significant developments in land treatment theory and practice, and to identify future research needs to address critical gaps in the knowledge base that must be addressed to ensure sustainable land application of residuals.

SINCE THE EARLY 1970s, scientists, engineers, regulators, and interested parties in the waste management field have met each decade to access the body of knowledge on land application of municipal wastewaters and sludges. Past themes include: "Recycling Municipal Sludges and Effluents on Land" (1973, Champaign-Urbana, IL); "Utilization of Municipal Wastewater and Sludges on Land" (1983, Denver, CO); and "Sewage Sludge: Land Utilization and the Environment" (1993, Bloomington, MN). Each conference resulted in major publications (National Association of State Universities and Land Grant Colleges, 1973; Page et al., 1987; Clapp et al., 1994) describing and critically evaluating the science that ultimately formed the basis for national regulations and guidelines for waste management. In January 2004, we convened what we intended to be a similarly effective, international conference, "Sustainable Land Application," in Orlando, FL. The conference addressed soil reactions of constituents in biosolids, effluents, manures, and other nonhazardous wastes (e.g., composts, water treatment residuals, food residues). The inclusion of manures and other nonhazardous wastes (referred to collectively hereafter as residuals) was an intentional broadening of the previous conference themes mentioned above. Often, residual constituent reactions in soils depend much more on the soil, and basic biogeochemical reactions therein, than on the residual. Thus, we felt that focusing on fundamental reactions, rather than specific residuals, would further sustainable land application of the residuals of modern society and would engage a wider array of scientists.

Mullin (2004) defines sustainability as the "triple bottom line" of economic prosperity, environmental stewardship, and corporate social responsibility. He argues that industries' newly focused plans for "reengineering" and "globalization" will ultimately fail without public trust in the safety of what the industries produce and/or do. Therefore, a more traditional description of sustainability that emphasizes applying residuals to land in a manner that protects human and animal health, safeguards soil and water resources, and maintains long-term ecosystem quality (Crites et al., 2000) is incomplete unless the earning of public trust is included. Thus, while the "Sustainable Land Application" conference focused on traditional "hard" science (e.g., soil chemistry, microbiology, and fertility), various speakers and conference participants also addressed public education, involvement, and trust issues.

This overview provides an introduction and partial synthesis of several papers and posters presented at the conference, as well as comments offered by conference participants. A complete listing of abstracts from all conference presentations is available on the conference website (www.conference.ifas.ufl.edu/landapp; verified 25 Aug. 2004). The conference was primarily sponsored by the USEPA, but a multitude of other national and state organizations and regulatory agencies provided generous support as well.

CONFERENCE OBJECTIVES AND TOPICS

The conference objectives were to:

- Review fundamental and specific soil reactions of nonhazardous residuals constituents.

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Published in J. Environ. Qual. 34:7–17 (2005).

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- Improve (and extend to various audiences) the understanding of contaminant reactions in soils, emphasizing the commonalities of soil reactions among residuals.
- Synthesize multidisciplinary information and characterize the "state-of-the-science" for land application. ("What do we know?")
- Identify high priority and critical research needs. ("What needs to be learned?")
- Promote intra- and interdisciplinary approaches to solving problems of residuals disposal or utilization in a sustainable manner.

Major programmatic topics included Nutrients, Metals, Organics, Pathogens, and Interpreting Science in the Real World. Plenary papers were presented for each topic, followed by invited, volunteered, and poster presentations that provided increasingly more detail for each topic.

TOPIC SUMMARIES

Several papers resulting from the presentations follow this overview. General summaries of each topic's "state-of-the-science" and research priorities are given below. Details are provided in the individual plenary papers on Nutrients (Pierzynski and Gehl, 2005), Metals (Basta et al., 2005), Organics (Overcash et al., 2005), Pathogens (Gerba and Smith, 2005), and Interpreting Science in the Real World (Bastian, 2005).

Nutrients

For more than 2000 yr, humans have land-applied a large variety of materials in an effort to supplement and/or improve the soil (Moss et al., 2002). Although commercial fertilizers supply most of the crop nutrient needs in the United States, manures, biosolids, composts, and other residuals are also used to supply nutrients and to improve soil properties (e.g., VanWieringen et al., 2005). Manures, in fact, are land-applied in the greatest amounts (>100 million dry Mg annually), about twice as much as commercial fertilizers (approximately 50 million Mg); biosolids (approximately 3–4 million Mg) and composts (approximately 0.5 million Mg) pale in comparison (Moss et al., 2002). Nutrient loads associated with each material, of course, vary with the material (e.g., fertilizers are the major source of nutrients, owing to the high elemental analysis), but residuals can be important and troublesome sources of nutrients such as N and P. Residuals applied at agronomic (typically, N-based) rates to farms near sensitive water bodies or residuals applied at very high rates ($\geq$50 Mg ha^{-1}) to reclaim drastically disturbed areas can threaten water quality. Clearly, land-applied residuals of all kinds can increase soil nutrient loads, and land application practices must consider nutrient fate and transport to be sustainable. Lessons learned about nutrient (e.g., N and P) reactions with manured soils (where most of the research has been done) should be transferable to concerns about N and P in biosolids, effluents, and composts as long as residual application rates do not overwhelm soil characteristics that determine the soil's assimilative capacity.

Advances in determining potentially available nitrogen (PAN), taking into consideration climate and soils data, have been made for biosolids (Gilmour et al., 2000), and can probably be applied to other residuals. However, the technique has not been verified for the myriad of other residuals, and much remains to be learned (Cabrera et al., 2005). Residual quality (N content) can vary significantly with time, which complicates accurate estimation of PAN and the resulting calculation of appropriate residuals application rates (Pierzynski and Gehl, 2005).

Phosphorus concerns associated with land application of residuals have precipitated extensive research interest recently. The water solubility of P in various residuals can vary (e.g., Sharpley and Moyer, 2000; Brandt et al., 2004), so different amounts of P are available for soil reaction, but the same soil P fixation reactions are logically expected to determine soluble P in most residuals-amended soils. Thus, P leaching in most soils in the United States is minimal regardless of P source (Sims et al., 1998). However, when the residuals are surface-applied, applied to soils with minimal P retention capacity, or applied at exceptionally high rates, residual properties (P solubility) tend to dominate soil characteristics. Differences in residual P solubility are expressed in less P leached (e.g., Elliott et al., 2002) or collected as runoff (e.g., Withers et al., 2001) from biosolids than fertilizer and manures.

While most of the nutrient research to date on residuals has focused on N and P, residuals containing other nutrients deserving consideration. Secondary nutrients (Ca, Mg, and S) exist in relatively high concentrations in biosolids, manures, and some compost and can be important sources in agronomic settings (Moss et al., 2002). For example, interactions with Ca and Mg can affect P solubility, both in the residual and in amended soils (Nair et al., 2003; Josan et al., 2005). Sulfur loads associated with even realistic biosolids application rates can increase Mo hazard (molybdenosis) to cattle grazing amended pastures (O'Connor et al., 2001). The micronutrient value of residuals, especially biosolids and manure, has been long appreciated (e.g., Mathers et al., 1980; McCaslin et al., 1987). However, some manure can also contain especially high concentrations of Cu and Zn that can cause plant and animal toxicities (Christie and Beattie, 1989). Logan et al. (1999) reported sufficiently high concentrations of B in some compost to raise phytotoxicity concerns with some plants.

Metals

Residuals (especially biosolids) are often regarded as major sources of potential metal pollutants despite the relatively small quantities of the residuals land-applied. Sims (1995) and Moss et al. (2002), however, point out that the trace element (metal) concentrations in some manures equal or exceed those in modern biosolids. Metal contents of biosolids have decreased dramatically since the USEPA established pretreatment discharge standards for numerous industrial categories in the 1980s (Stehouwer et al., 2000). Some fertilizers contain high concentrations of trace elements ("heavy metals"), although the much smaller application rates of commercial fertilizers (compared with biosolids and manures) results in much smaller metal loads from such fertilizers to soil.

While total metal loads applied in residuals to soils are important (regulations frequently dictate allowed total metal loads), research on many fronts has repeatedly shown that metal solubility and availability is most important (Basta et al., 2005). Soil reactions such as sorption and precipitation and metal speciation play critical roles in determining metal solubility and bioavailability. However, the residual itself can also provide significant metal retention and solubility and speciation control, thereby limiting metal bioavailability (Basta et al., 2005), which may produce the "plateau effect," first espoused by Corey et al. (1987). Such residual effects on metal solubility also mean that studies of residual-metal availability must be conducted using residual-borne metals, not in soils spiked with metal salts. Similarly, studies should be conducted with modern, low-metal residuals rather than the highly contaminated residuals characteristic of years past, because such highly contaminated residuals reflect metal availabilities more closely representative of metal salts than modern residuals. While sufficient research has been conducted to demonstrate these differences in metal behavior when biosolids- or compost-bound, manure-metal reactions may be very different in some soils because manures frequently lack the solid-phase components of biosolids. Regardless of the metal source, soil reactions (mentioned above) can be expected to play important roles in determining metal bioavailability. The pH of the soil-residual system is often the most important property governing metal availability (Basta et al., 2005).

Metals research over the past several decades has focused primarily on the trace element cations regulated in biosolids (Ni, Cu, Zn, Cd, Pb, Hg). The anionic trace elements (As, Mo, Se) have received less attention, but important differences in the soil chemical reactions of the two groups are recognized, especially the difference in elemental solubility and soil adsorption with pH (Basta et al., 2005). Knowledge of the nature (form, solubility, charge) of trace elements in residuals is fundamental to understanding the fate and transport of all residuals-borne trace elements and to prescribing management techniques. For example, the general practice of raising soil pH to reduce trace metal cation solubility, bioavailability, and mobility in soil–plant systems is counterproductive in managing trace metal anions in residuals-amended soils. Some residuals (e.g., water treatment residuals, high Fe- and/or Al-biosolids) can significantly reduce P solubility, despite significant residuals-associated P loads, and reduce P runoff and leaching (Maguire et al., 2001; Peters and Basta, 1996; Elliott et al., 2002). The same sorbing solids that retain P should have similar effects on other oxyanion constituents (As, Mo, and Se) in various residuals.

Before a 1998–2000 survey (Interagency Steering Committee on Radiation Standards, 2003), little information was available on radionuclides (mostly metals) in biosolids. Dose modeling using results of the survey suggest minimal effects of biosolids-associated radionuclides on human health and the environment in most situations (Bastian et al., 2005).

Organics

Chemicals in commerce represent approximately 90 000 specific organic compounds that are potential constituents of societal residuals. A huge range of chemical properties (e.g., solubility, volatility, resistance to degradation, adsorptive behavior) is represented. This seemingly endless supply of compounds, together with the variety of reactions they can undergo, makes describing the human, animal, and environmental effects of organics exceptionally challenging, a fact recognized years ago (Ryan et al., 1988). Chemicals of concern are traditionally those that are persistent in the environment and/or toxic to humans and animals. Persistent organic chemicals can become associated with residuals of all kinds through a variety of mechanisms, including aerial deposition, runoff into urban drains, industrial effluents, household domestic wastewater, administration of drugs to humans and other animals, and possible formation in treatment plants. Most early research effort on organic chemicals of commerce focused on persistent organics in biosolids (e.g., Jacobs et al., 1987; Webber and Lesage, 1989; O'Connor et al., 1991). The consensus of early research effort was that biosolids-borne toxic organics risk was meaningfully quantifiable and that the risk was small for most of the priority pollutants (e.g., Chaney, 1990a, 1990b). Such confidence and the low concentration of priority pollutants measured in the National Sewage Sludge Survey (USEPA, 1990) led the USEPA to drop organics from Part 503 regulations for land application of biosolids. Limited field data (e.g., Witte et al., 1988), however, were available in the early 1990s to confirm risk calculations under real-world conditions. Most data sets were greenhouse or small-plot studies, laboratory incubations or column studies, or modeling efforts; all frequently suffered from analytical limitations to some degree.

More recent studies, using advanced analytical techniques, have renewed interest in various organics in biosolids (e.g., Stevens et al., 2003; Hale et al., 2001; Chaney et al., 1996), manures (e.g., Karpati and Rubin, 1998; Shore et al., 1995; Stevens and Jones, 2003), composts (Bezdicek et al., 2001; Laine and Jorgensen, 1997), effluents (e.g., Fox, 2002; American Water Works Association Research Foundation, 2001), and fertilizers derived from industrial residuals (Washington State Department of Ecology, 1999). Compounds of interest now extend beyond the "traditional" chemicals (e.g., polychlorinated biphenyls [PCBs], polycyclic aromatic hydrocarbons [PAHs], phthalate esters, pesticides, volatile aromatics) to include antibiotics, endocrine disruptors, flame retardants, and personal care products (Xia et al., 2005). A much more thorough evaluation of dioxin and furan residues culminated in a recent USEPA decision not to regulate dioxins in biosolids (USEPA, 2003a).

The renewed interest in residuals-borne organics has both confirmed and challenged previous attitudes. The concentrations of most "traditional" chemicals of concern (COC) in most residuals and residuals-amended lands are low, and prudent residuals land application (realistic residual application rates that do not exceed the soils' assimilative capacity) result in minimal risk to humans, animals, and the environment (Kester et al., 2005; Overcash et al., 2005). Our knowledge of (and appreciation for) newer COC, however, is incomplete. Additional, and widespread, analysis of residuals is necessary (Water Environment Research Foundation, 2003), greater attention to possible enhanced chemical movement in some soils (e.g., via preferential flow) deserves attention (Camobreco et al., 1996), and improved risk assessment is required (National Research Council, 2002; Schoof and Houkal, 2005). Although the "surrogate chemical" approach is valuable for addressing possible reactions and fates of the seemingly endless array of COC, specific chemical–soil–target organism combinations are necessary in some situations (Overcash et al., 2005). A chemical's degradation rate in soil remains the primary determinant of chemical fate, transport, and risk. Greater attention to measuring these rates is necessary. Field studies at multiple scales (e.g., Wilson et al., 1997; Beulke et al., 2000), rather than laboratory incubations, are necessary to confirm expectations (models) and to accurately access COC fate, transport, and risk.

Pathogens

Infectious disease–causing organisms (pathogens) enter a community's wastewater from hospitals, homes, schools, nursing facilities, etc. Animal wastes or manures can contain zoonotic organisms (organisms that can cause diseases in both animals and humans) and enter wastewaters from farms, meat packing and processing facilities, and from animals and/or vectors found around sewage or sewers. Manures, by virtue of the greater application masses than biosolids, are even greater sources of pathogens, including the same types of organisms (bacteria, viruses, and protozoa), than human wastes (Moss et al., 2002). Unlike biosolids, the number of pathogens in manures is not strictly regulated. Humans can come in contact with pathogens by direct contact with biosolids or manure by eating food or drinking water contaminated with residuals, through contact with individuals or vectors that have been in contact with the residuals, and possibly via bioaerosols from land application of residuals (Gerba and Smith, 2005).

During typical wastewater treatment, microorganisms become concentrated in the sewage sludge. Federal regulations (40 CFR, Part 503) require sewage sludge to be treated with processes to significantly reduce pathogens (PSRPs) or processes to further reduce pathogens (PFRPs) before land application as biosolids (treated sewage sludge). Land application of PSRP (Class B) materials must also be accompanied by access, grazing, and/or crop harvesting restrictions and a vector attraction reduction process. Land applications of PFRP materials (Class A biosolids, assumed to be essentially pathogen free) have no access, grazing, or harvesting restrictions. The U.S. pathogen and vector attraction reduction requirements are regarded as performance based. Most Class A alternatives (including the PFRP processes) have demonstrated ability to reduce enteric viruses and helminth ova to below the analytical detection limit. All Class A products must be tested and show either that *Salmonella* sp. are nondetectable or fecal coliforms are present at levels of $<$1000 cfu g^{-1}. Class B PSRP processes require no testing for the presence of organisms. Class B, Alternative 1 gives facilities that do not have a PSRP process the alternative of testing the treated sludge for fecal coliforms and showing that the level is $<$2 000 000 cfu g^{-1}. The accuracy and appropriateness of the assays have been questioned. It is essential that methods for analyzing the organisms be standardized and validated as quickly as possible (Gerba and Smith, 2005). Fortunately, lower levels of pathogens, including *Salmonella* sp., enteric viruses, and helminth ova, are found in untreated sludges today than were found two or three decades ago (Gerba and Smith, 2005). Treatment plants produce better quality (lower pathogen content) materials today than before because of improved attention to, and control of, the critical process parameters like digestion temperature and time (Godfree and Farrell, 2005).

Assessment of risks associated with land-applied biosolids has relied on in-plant treatment schemes and has been influenced by the lack of documented cases of illness following decades of land application of biosolids or in treatment plant operators. Numerous public complaints and anecdotal reports of serious illness (including deaths) associated with biosolids land application operations have fueled renewed interest in validating treatment effectiveness and modern risk assessment. A recent National Research Council (2002) report supported these calls. Increased globalization, with the associated greater movement of people internationally, changes in food production, and changing demography all contribute to our seeing more "emerging" pathogens (SARS, Asian flu viruses), so more work is needed on pathogen evaluation, source tracking, treatment effectiveness, and risk assessment (Smith et al., 2004).

Little experience is available for conducting a quantified microbial risk assessment, and successful evaluations require better data on infectious dose and the survival and transport of specific organisms during land application. Gale (2004) illustrated one approach, using a "prototype event tree" for risk assessment for *Salmonella* on potatoes. Eisenberg et al. (2004) demonstrated a framework that considers health effects, including immunity and secondary infection. Additional, modern risk assessments and improved exposure data for model input are needed.

Quantification of microorganism transport off-site via bioaerosols and subsequent infection of people downwind has generated much public concern, but limited scientific attention. Dowd et al. (2000) showed that airborne pathogens were a potential risk to workers at biosolids application sites, although the risk was small. The data suggest that biosolids microbes stay with sludge particles and fall out shortly after the biosolids is applied, minimizing bioaerosols effect. Rusin et al. (2003) estimated minimal risk from *Staphylococcus aureus* in sludge, as *S. aureus* was found in untreated sludge but never in treated sludge or aerosols sampled. Despite these encouraging results, further research is necessary to reassure the public; pertinent field studies are ongoing (Gerba and Smith, 2005).

Both biosolids and manures contain pathogens, but only biosolids are required to be treated with processes to significantly reduce pathogens. Manures can be major sources of pathogens to the environment; a United Kingdom study found that manures contributed more *Salmonella* to the environment than biosolids. The same study found that wild animals and birds contribute to ambient pathogen levels, including *Cryptosporidium* oocysts (Drury and Lloyd, 1997). To date, no case of pathogen-related health effects from biosolids has been documented, but manures have been implicated in several pathogen-related outbreaks in North America (Moss et al., 2002; Smith et al., 2004). A limited number of studies have demonstrated bacteria and parasite transport to ground water and surface waters near manure application areas (references cited in Moss et al., 2002). This is not an expected or normal happening. For bacteria and parasites to move to ground water there needs to be some sort of direct hydrologic connection and little or no possibility of the solution percolating through soil that acts as a filter. Likewise for pathogens to move to surface water, the solution velocity has to be high with little opportunity for settling to occur or for filtration as the solution moves through vegetative cover. Clearly, pathogen fate, transport, and risk assessment is as critical for manure-borne pathogens as for those borne by biosolids.

Interpreting Science in the Real World

The design guidance, regulations, and management practices currently employed by modern sustainable land application projects have evolved from many years of research and demonstration efforts as well as experience with both pilot- and field-scale projects.

Such efforts have demonstrated the beneficial and sustainable use of residuals on productive farmland, forests, marginal lands, drastically disturbed areas, and even highly contaminated sites (Jacobs et al., 1993; Brown et al., 2005).

Science and the available technical information are only part of what goes into developing sustainable land application projects and their applicable regulatory requirements and management practices in the real world. The controls imposed on land application practices are generally aimed at protecting public health and the environment, but also must take into account such factors as available control technologies, cost-effectiveness, public policy objectives, public acceptance and, of course, political realities.

The importance of public involvement and the need to gain and maintain public acceptance in maintaining sustainable land application projects simply cannot be overstated (Beecher et al., 2005). Frequently, the initial basis for local concerns has been linked to the production of odors and/or nuisance conditions (e.g., noise, dust, flies, truck traffic). Traditionally, odor has been regarded primarily as a nuisance issue, but the health effects of odors are now receiving rigorous scientific study (Schiffman and Williams, 2005).

Voluntary partnerships, which actively involve potentially affected and interested stakeholders early on in the development and implementation of sustainable land application practices, can avoid problems that might otherwise be overlooked until it is too late (T. Evans and N. Lowe, personal communication, 2004).

Legislative efforts can encourage safe and beneficial recycling of residuals and provide guidance and regulatory requirements. Well-established formal rule-making process requirements must be followed during the development of regulations. The basic paradigm used for human health risk assessment—hazard identification, dose–response assessment, exposure assessment, and risk characterization (National Research Council, 1983)—has become the usual framework behind the development of many of the regulations in the United States, although less so in Europe. While the regulatory agencies are generally committed to using sound science in decision-making, many other equally important factors influence the process, including implementation costs, technical feasibility, economic effects on small businesses, and social and political considerations (R. Parry and M. Whitworth, personal communication, 2004). At least some of the constraints on agricultural land application practices created by the various regulations and local requirements can be overcome when projects are established that help deal with high visibility environmental problems such as the restoration, revegetation, and rehabilitation of highly disturbed and contaminated sites (Brown et al., 2005). The benefits, as well as the risks, of land-applying residuals should be thoroughly documented (e.g., Moss et al., 2002).

Extensive information is currently available on many issues associated with land application practices, but further research in a number of areas could lead to better information and tools to improve our design, operation, management, and regulation of sustainable land application systems (Bastian, 2005). We should document successes achieved by applying various regulatory controls and best management practices (BMPs) vs. natural cycles affecting the fate of nutrients (Koelsch, 2005), pathogens, inorganics, and persistent organic pollutants. We should develop more effective outreach materials (e.g., detailed reports, brochures, one page fliers) on technical issues associated with sustainable land application practices. An example is the Agricultural Phosphorus and Eutrophication brochure developed jointly by the USDA-ARS and USEPA (Sharpley et al., 2003) that communicates with both scientific and lay audiences. Such documents may aid in identifying various techniques to reduce public opposition, including mechanisms to promote dialog, educate the public, and increase stakeholder involvement. Fundamental to success is facilitation of more public interaction and interfacing with solid waste management programs.

Better odor management models and guidance documents are needed, including better information on the levels of, and sensitivities of individuals to, bioaerosols, odors, and chemicals associated with land-applied residuals. Guidance materials that go beyond meeting confined animal feeding operation (CAFO) regulatory requirements (e.g., BMPs for odor management, ground water protection, reducing air emissions, pathogen reduction, and metals) are necessary.

Environmental lifecycle analyses of sustainable land application projects, including evaluation of all inputs (e.g., energy, chemicals, etc.) and ultimate fate of contaminants (e.g., nutrients, inorganic and organic compounds, and pathogens), should be undertaken. These could lead to the development of renewable energy project initiatives (e.g., subsidies, grid purchase back requirements) to facilitate CAFO integrator supported Green Power projects and marketing of power to their own producers. Consideration could also be given to using credits for C sequestration, restoration, etc. (Fox et al., 2005).

COMMONALITY OF REACTIONS

Regardless of the contaminant or residual applied, the same soil processes and reactions ultimately determine contaminant fate, transport, and risk. The process and reactions can be categorized as retention (adsorption, precipitation, absorption), transformation (degradation, volatilization, oxidation–reduction, speciation), and movement (leaching, runoff and erosion, aerosolization). While there can be important matrix effects associated with residual solid and chemical properties, the basic soil processes and reactions can logically be expected to apply to a particular contaminant regardless of the residual carrying the contaminant into the soil. Indeed, soil reactions of contaminants in the residuals can be considered key to sustainable land application systems (Bastian, 2005). The soil and its associated microorganisms and vegetation typically react to the *specific* nutrient, organic matter, heavy metal, inorganic and organic contaminant, or pathogen additions and can modify the form of the contaminant through direct oxidation–reduction reactions, adsorption–desorption, biodegradation, and plant uptake. In some cases the reactions are temporary, while in other cases reactions are essentially permanent, unless the overriding factors controlling the soil properties are changed by external sources. Thus, scientists do not need to "reinvent the wheel" by studying the fate of each and every contaminant that may be present in each and every waste source to at least qualitatively predict how they will behave in land application systems with time. Similarly, the good management practices, best alternative technologies, and scientific consensuses that drive land application of some residuals (manures and biosolids) can logically be applied to other residuals (Bastian, 2005).

COMMON THEMES SHAPING FUTURE RESEARCH

The conference papers that follow detail high-priority and critical research needs in the specific areas of nutrients, metals, organics, pathogens, and translating science into practice. In the process of identifying future research needs to promote sustainable land application, several themes repeatedly emerged. These themes are crosscutting and applicable to the major categories around which the conference was structured.

Field-Scale Studies

During the last three decades, numerous scientific studies have generated a large body of information on the environmental effects and benefits associated with land application of residuals and wastewaters (Bastian, 2005). More than 2000 technical papers have been published regarding land application of biosolids alone. Much of the research has been conducted at the laboratory or greenhouse scale where environmental conditions are controllable. Such studies are very effective for investigating the influence of individual factors. Data collection is facilitated because experiments are not subject to the uncertainty associated with climate and other factors over which there is little or no control.

However, results from laboratory and greenhouse conditions frequently do not extrapolate to field conditions. Short-term greenhouse pot experiments are often not valid to assess soil-to-plant trace element transfer in the field (deVries and Tiller, 1978). The persistence of organic pollutants in the field is often overestimated by models based on laboratory-determined degradation half-lives (Beulke et al., 2000). Preferential flow, where water bypasses the soil matrix, is an important pollutant transfer mechanism that cannot be evaluated with disturbed soils in laboratory or greenhouse conditions (e.g., Camobreco et al., 1996).

There is a broad consensus that future efforts should stress the performance of full-scale land application sites rather than laboratory-generated information. Although field studies inherently involve high cost and the risk of failure for reasons beyond the control of the researcher, field studies offer the ultimate scenario for addressing problems. Some important questions, like the effectiveness of vegetated buffer strips in protecting water quality (Entry et al., 2000) and the extent of bioaerosol production, cannot be realistically answered except through field experiments. Long-term studies are particularly valuable to document sustainability of application practice and provide information on long-term environmental effects.

While there have been a number of long-term studies (Bastian, 2005), additional studies are needed. The investigations should be well designed, comprehensive, regionally sensitive studies using residuals and application rates and conditions that meet current regulations and guidance. There should be a common minimum set of measured parameters to facilitate cross-study comparisons and modeling efforts. One of the 14 specific projects targeted in the USEPA's final action plan responding to the National Research Council Biosolids

Report Recommendations addressed "field studies of application of treated biosolids" (USEPA, 2003b). Similarly, a key need identified in the Water Environment Research Foundation–sponsored Biosolids Research Summit was a project to "evaluate the effectiveness of current 503 regulations and other management practices" (Water Environment Research Foundation, 2003).

Such field studies would necessarily be multidisciplinary and comprehensive in nature and involve impact assessment for soils, vegetation, ground water, soil microbial populations, and air quality. They could provide opportunity to conduct epidemiological studies of exposed populations. These holistic studies should be coordinated and conducted at several locations to address regional differences in climatic, soil, and geomorphologic conditions.

Ecosystem Responses

Past research and regulatory efforts have largely focused on managing soil pollutants to minimize adverse effects on human health via water supplies and the food chain. While some investigations have been conducted on the effect of residuals on microorganisms (Angle, 1998; B. Chambers, personal communication, 2004), there is limited understanding of the effect of residuals on many other receptors in soil ecosystems or the ability of residuals to reduce or eliminate ecotoxicity in heavily contaminated soils (Brown et al., 2005). Land application effects on indigenous microbial populations, invertebrates, and wildlife have received insufficient attention.

The effects of land application on organism health and important biological processes (organic residue recycling, nitrogen fixation, respiration) need to be more fully documented. Ecological risk assessment should be used to establish guidelines for land application of residuals (Basta et al., 2005). This necessitates evaluation of applicability and validity of existing ecological models to residuals-amended soils.

The ability of residuals to restore ecosystem function in drastically disturbed landscapes needs to be more fully studied and publicized. Residuals can beneficially affect ecosystems damaged by forest fires, overgrazing, smelting, coal and mineral mining, and fly ash and mine tailings storage. Because of the large areas of many degraded landscapes, huge quantities of residuals are needed for reclamation. Because much greater residual loads are typically used in reclamation efforts, effects on microbial communities, higher-level microorganisms (nematodes), earthworms and other invertebrates, and small mammals need to be addressed. Methods for obtaining diversity indices (e.g., Biolog substrate utilization) will be useful tools in studying ecosystem responses. Various bioassay techniques provide a well-developed means of evaluating bioavailability and acute toxicity of soil contaminants (Conder et al., 2001).

Additional Constituents of Concern

Common among the contaminant categories is the recognized need to expand coverage to a wider array of constituents. This theme is not new, as evident in the case of nutrients. Despite a very early recognition that conventional practice results in overapplication of phosphorus (National Association of State Universities and Land Grant Colleges, 1973), Part 503 dictated that the application rate for biosolids be determined by the agronomic N need. However, widespread concern over surplus soil P has led to a major shift in research resources toward addressing P reactions and loss potential from residual-amended fields. Pending regulatory changes could dramatically affect land application of manures, biosolids, and other P-containing residuals (Brandt et al., 2004; Shober and Sims, 2003). The bioavailability of other residual-borne nutrients (S, Ca, Mg, micronutrients) may also need more detailed study.

The evolution of targeted constituents warranting rigorous scientific evaluation [identified by improved risk assessment (Schoof and Houkal, 2005)] is clearly apparent for organics and elemental pollutants. Recently, in response to a mandate in section 405(d)(2)(C) of the Clean Water Act, the USEPA reviewed biosolids regulations and identified additional pollutants for potential regulation. Fifteen pollutants were identified for review: acetone, anthracene, Ba, Be, carbon disulfide, 4-chloroaniline, diazinon, fluoranthene, Mn, methyl ethyl ketone, nitrate, nitrite, phenol, pyrene, and Ag (USEPA, 2003b). Other trace elements, including Tl, W, and V (Basta et al., 2005), as well as B and F (Harrison et al., 1999), are candidates for evaluation using Part 503 risk assessment methods. *N*-nitrosodimethylamine (NDMA) is a suspected human carcinogen, is present in treated effluents, and is a potential ground water pollutant (Mitch and Sedlak, 2004). Hale et al. (2001) proposed that the environmental consequences of brominated diphenyl ethers (BDEs), compounds widely used in flame retardants, be investigated in biosolids–soil systems. Other residuals may contain additional contaminants warranting further study, especially manures, for which the database on organics is much more limited than biosolids.

The pollutant group that has recently captured the attention of the public and regulatory community is a category of compounds called endocrine disruptors. These are found in pharmaceuticals, personal care products, plastics, pesticides, manures, and industrial by-products and can interfere with natural hormones, causing reproductive and growth problems in animals, particularly aquatic organisms (Xia et al., 2005). While many of these chemicals are rapidly biodegraded in soils, water quality concerns dictate a fuller understanding of their fate and transformations in land application systems. A key need is the development, validation, and application of analytical methods for detecting pharmaceuticals and personal care products in soils, manures, and biosolids (USEPA, 2003b).

Advancing standards and practice for sustainable land application must address the paramount need to protect public health from emerging infectious disease agents. The traditional use of fecal coliform as an indicator organism reflected the overriding concern to address transmission of enteric pathogens between humans. A fuller appreciation of microbial risks must also address the numerous microbial pathogens that can be transmitted from animals to humans (zoonotic diseases). New organisms of concern were identified (Smith et al., 2004), including bacteria (*E. coli* 0157:H7, Listeria, Heliobacter), viruses (poliovirus, Coxsackievirus, Echovirus, Hepatitus A, Rotavirus, Norwalk), and parasites (Cryptosporidium, Cyclospora, Toxoplasma, Microsporidia, Balantidium, Giardia, Entomoeba). The database for the concentrations of these organisms in manures and biosolids is small and should be expanded (Moss et al., 2002).

New Analytical Techniques

Understanding the fundamental processes controlling pollutant transformations, effects, and fate in land application systems hinges on the reliability and detection capabilities of analytical procedures. Much of the current knowledge is based on inferences from macroscopic observations of solution composition, thermodynamic equilibrium models, and operationally defined chemical fractionation procedures. Advancements in analytical methods and data handling techniques are needed to refine the fundamental mechanistic understanding of constituent processes and reactions in soil–plant systems. Rapid and sensitive methods that allow simultaneous multicomponent analysis in both liquid (inductively coupled plasma, ICP) and solid (energy dispersive X-ray fluorescence, EDXRF) samples enhance the speed with which environmental data can be collected.

Particularly useful in future research will be advanced spectroscopic techniques to elucidate pollutant speciation and identify solid-phase transformations. X-ray absorption near-edge structure (XANES) spectroscopy has been used to identify the dominant solid-phase P species in soils (Beauchemin et al., 2003). Synchrotron radiation–based Fourier transform infrared (SR-FTIR) spectromicroscopy has the potential to monitor real-time microbial processes (R.C. Sims and J.K. Nieman, personal communication, 2004). Extended X-ray absorption fine structure (EXAFS) can be used to study metal speciation in plant roots and leaves (Sarret et al., 2001).

The area of pathogens is one with significant needs for improved and advanced analysis techniques and validation. Sampling strategies for field-testing of indicator organisms and pathogens are needed. The microbiological methods for *Salmonella* spp., enteric viruses, and helminth ova, which serve as the basis for current regulations, still require standardization and validation. Detection methods need to be developed for the numerous emerging infectious agents. Advanced techniques (DNA sequencing, polymerase chain reaction [PCR]) and principal component analysis may prove useful to identify and characterize changes in microbial communities in soils and residuals. An absolute standard for vector attraction reduction needs to be developed.

Other Residuals

Residuals and residuals-borne contaminants are subject to the same soil processes and reactions that ultimately determine contaminant fate, transport, and risk. There can be, however, important matrix effects associated with the residual chemical, mineralogical, and biological properties. For example, distribution and mobility of trace elements can be strongly influenced by residual mineralogical composition. In some waste matrices, certain minerals can dissolve, providing a latent source of pollution (Laperche and Bigham, 2002).

Efforts must, therefore, broaden to residuals other than manures, biosolids, and municipal wastewaters and address co-application of residuals. An expanded regulatory framework needs to be designed to encourage safe, sustainable, well-managed programs for a wider variety of residuals and effluents. We do not have guidelines that set trace element loadings for land application of many nonbiosolids residuals. By default, some states are using Part 503 standards for nonbiosolids residuals. However, given the potential importance of matrix effects, the risk analysis done for biosolids is not always applicable to other residuals.

Many municipal, agricultural, and industrial wastes are routinely spread on soils, yet there are no universally accepted standards for land-based disposal and recycling. Environmental and economic constraints on landfilling or stockpiling have increased interest in land application of many residuals and by-products. Pulp and paper residues, ashes from wood- and coal-fired boilers, fly ash, flue-gas desulfurization by-products, and petrochemical residuals are routinely land-applied. By-products from food processing that are not incorporated into animal feeds are often surface spread, but few have been thoroughly researched. Coagulation and softening residuals from drinking water purification can be beneficially applied to soils as P control agents or lime substitutes. There are no federal guidelines for land application of these residuals, and state regulations are either nonexistent or are highly variable between states. Research is needed on factors on which to base guidelines for the disposal and safe use of these by-products.

Besides investigating single waste types, the co-application of residual types warrants study. Numerous residual streams present opportunities for co-utilization, or the deliberate blending, of by-products (see Brown et al., 1998). Mingling residuals on the soil can both increase and decrease the environmental mobility of the constituents. Applications of water treatment residuals are effective in decreasing the leaching (Elliott et al., 2002) and runoff (Haustein et al., 2000) of P contained in co-applied biosolids or manures. Manure additions to fly ash enhance the bioavailability of P in the fly ash (Bhattacharya and Chattopadhyay, 2002). Mixing C- and N-rich residuals to achieve a C to N ratio that does not lead to nitrate leaching even at higher than agronomic application rates is a technique that holds promise (Gilmour, 1998).

Interfacing with the Real World

Science and technical information is only part of developing and managing sustainable land application practices. An important conclusion from the 1973 conference was that "unless political and institutional constraints on the land application of effluents and sludges are recognized, identified, and resolved, projects will likely fail, regardless of their technical, scientific, and economic feasibility" (National Association of State Universities and Land Grant Colleges, 1973). Experience over the past three decades has borne this out. Major national trends underscore the urgency to appreciate community concerns. Census data document a migration of urban residents to rural areas coupled with an accelerating loss of farmland. The population continues to expand, meaning more municipal wastes, as well as agricultural residues from food production, are generated. Food processing and livestock production facilities have become larger and more concentrated as well.

A recurring conference theme was the need to conduct research with an acute awareness of stakeholder (the public, agricultural organizations, and conservation and regulatory personnel) concerns and community needs. Researchers must understand public concerns about odors and other nuisances, issues that may not be readily amenable to conventional human health risk assessment paradigms. Consideration of stakeholder issues must occur, not as an afterthought, but early on in the conceptualization and prioritization of research agendas. Public participation efforts must involve active listening on the part of researchers. There must also be a concerted effort to improve communication of findings to stakeholders. Researchers must be able to translate scientific findings and research outcomes into language appropriate to the public and regulatory personnel.

As researchers in the field, our task is to provide information that advances the continual improvement in the design, performance, reliability, and safety of land application systems. Research endeavors to promote the sustainability of such systems will largely be wasted without due consideration and active implementation of stakeholder concerns. The vital societal importance of the soil as a disposal and recycling medium for an increasing volume and array of residuals makes such efforts imperative.

REFERENCES

American Water Works Association Research Foundation. 2001. Soil aquifer treatment for sustainable water reuse. AWWARF, Denver.

Angle, J.S. 1998. Impact of biosolids and co-utilization wastes on rhizobia, nitrogen fixation and growth of legumes. p. 235–245. *In* S. Brown, J.S. Angle, and L. Jacobs (ed.) Beneficial co-utilization of agricultural, municipal, and industrial by-products. Kluwer Academic Publ., Dordrecht, the Netherlands.

Basta, N.T., J.A. Ryan, and R.L. Chaney. 2005. Trace element chemistry in residual-treated soil: Key concepts and metal bioavailability. J. Environ. Qual. 34:49–63 (this issue).

Bastian, R.K. 2005. Interpreting science in the real world for sustainable land application. J. Environ. Qual. 34:174–183 (this issue).

Bastian, R.K., J.T. Bachmaier, D.W. Schmidt, S.N. Salomon, A. Jones, W.A. Chiu, L.W. Setlow, A.W. Wolbarst, C. Yu, J. Goodman, and T. Lenhart. 2005. Radioactive materials in biosolids: National survey, does modeling, and Publicly Owned Treatment Works (POTW) guidance. J. Environ. Qual. 34:64–74 (this issue).

Beauchemin, S., D. Hesterberg, J. Chou, M. Beauchemin, R.R. Simard, and D.A. Sayers. 2003. Speciation of phosphorus in phosphorus-enriched agricultural soils using X-ray absorption near-edge structure spectroscopy and chemical fractionation. J. Environ. Qual. 32:1809–1819.

Beecher, N., L.E. Harrison, N. Goldstein, M. McDaniel, P. Field, and L. Susskind. 2005. Risk perception, risk communication, and stakeholder involvement for biosolids management and research. J. Environ. Qual. 34:122–128 (this issue).

Beulke, S., I.G. Dubus, C.D. Brown, and B. Gottesbüren. 2000. Simulation of pesticide persistence in the field on the basis of laboratory data—A review. J. Environ. Qual. 29:1371–1379.

Bezdicek, D., M. Fauci, D. Caldwell, R. Finch, and J. Lang. 2001. Persistent herbicides in compost. BioCycle 42:25–53.

Bhattacharya, S.S., and G.N. Chattopadhyay. 2002. Increasing bioavailability of phosphorus from fly ash through vermicomposting. J. Environ. Qual. 31:2116–2119.

Brandt, R.C., H.A. Elliott, and G.A. O'Connor. 2004. Water-extractable phosphorus in biosolids: Implications for land-based recycling. Water Environ. Res. 76:121–129.

Brown, S., J.S. Angle, and L. Jacobs (ed.) 1998. Beneficial co-utilization of agricultural, municipal, and industrial by-products. Kluwer Academic Publ., Dordrecht, the Netherlands.

Brown, S., M. Spenger, A. Maxemchuk, and H. Compton. 2005. Ecosystem function in alluvial tailings after biosolids and lime addition. J. Environ. Qual. 34:139–148 (this issue).

Cabrera, M.L., D.E. Kissel, and M.F. Vigil. 2005. Nitrogen mineralization from organic residues: Research opportunities. J. Environ. Qual. 34:75–79 (this issue).

Camobreco, V.J., B.K. Richards, T.S. Steenhuis, J.H. Peverly, and M.B. McBride. 1996. Movement of heavy metals through undisturbed and homogenized soil columns. Soil Sci. 161:740–750.

Chaney, R.L. 1990a. Research provides basis for quantitative risk assessment to make appropriate regulations for land application of sewage sludge: 1) Twenty years of land application research. BioCycle 31:54–59.

Chaney, R.L. 1990b. Research provides basis for quantitative risk assessment to make appropriate regulations for land application of sewage sludge: 2) Public health and sludge utilization. BioCycle 31:68–73.

Chaney, R.L., J.A. Ryan, and G.A. O'Connor. 1996. Organic contaminants in municipal biosolids: Risk assessment, quantitative pathway analysis, and current research priorities. Sci. Total Environ. 185: 187–216.

Christie, P., and J.A.M. Beattie. 1989. Grassland soil microbial biomass and accumulation of potentially toxic metals from long-term slurry application. J. Appl. Ecol. 26:597–612.

Clapp, C.E., W.E. Larson, and R.H. Dowdy (ed.) 1994. Sewage sludge: Land utilization and the environment. SSSA, Madison, WI.

Conder, J.M., R.P. Lanno, and N.T. Basta. 2001. Assessment of metal availability in smelter soil using earthworms and chemical extractions. J. Environ. Qual. 30:1231–1237.

Corey, R.B., L.D. King, C. Lue-Hing, D.S. Fanning, J.J. Street, and J.M. Walker. 1987. Effects of sludge properties on accumulation of trace elements by crops. p. 25–51. *In* A.L. Page, T.J. Logan, and J.A. Ryan (ed.) Land application of sludge—Food chain implications. Lewis Publ., Chelsea, MI.

Crites, R.L., S.C. Reed, and R.K. Bastian. 2000. Land treatment systems for municipal and industrial wastes. McGraw-Hill, New York.

deVries, M.P.C., and K.G. Tiller. 1978. Sewage sludge as a soil amendment, with special reference to Cd, Cu, Mn, Pb, and Zn—Comparison of results from experiments conducted inside and outside a greenhouse. Environ. Pollut. (1970–1979) 16:213–240.

Dowd, S.E., C.P. Gerba, I.L. Pepper, and S.D. Pillai. 2000. Bioaerosol transport modeling and risk assessment in relation to biosolids placement. J. Environ. Qual. 29:343–348.

Drury, D.R., and A. Lloyd. 1997. Cryptosporidium—A regulator's viewpoint. p. 369–375. *In* C.R. Fricker (ed.) Int. Symp. on Waterborne Cryptosporidium Proc., Newport Beach, CA. 2–5 Mar. 1997. Am. Water Works Assoc., Denver.

Eisenberg, J.N.S., J.A. Soller, J. Scott, D.M. Eisenberg, and J.M. Colford. 2004. A dynamic model to access health risks associated with beneficial uses of biosolids. *In* J.E. Smith, Jr., et al. (ed.) Contemporary perspectives on infectious disease agents in sewage sludge and manure. The JG Press, Emmaus, PA.

Elliott, H.A., G.A. O'Connor, and S.R. Brinton. 2002. Phosphorus leaching from biosolids-amended sandy soils. J. Environ. Qual. 31: 681–689.

Entry, J.A., R.K. Hubbard, J.E. Theis, and J.J. Fuhrmann. 2000. The influence of vegetation in riparian filter strips on coliform bacteria: I. Movement and survival in water. J. Environ. Qual. 29:1206–1214.

Fox, P. 2002. Soil aquifer treatment: An assessment of sustainability. Manage. Aquifer Recharge Sustain. 1:21–29.
Fox, P., W. Aboshanp, and B. Alsamadi. 2005. Analysis of soils to demonstrate sustained organic carbon removal during soil aquifer treatment. J. Environ. Qual. 34:156–163 (this issue).
Gale, P. 2004. Pathogens in biosolids—Microbial risk assessment. *In* J.E. Smith, Jr., et al. (ed.) Contemporary perspectives on infectious disease agents in sewage sludge and manure. The JG Press, Emmaus, PA.
Gerba, C., and J.E. Smith, Jr. 2005. Sources of pathogenic microorganisms and their fate during land application of wastes. J. Environ. Qual. 34:42–48 (this issue).
Gilmour, J.T. 1998. Carbon and nitrogen mineralization during co-utilization of biosolids and composts. p. 89–112. *In* S. Brown, J.S. Angle, and L. Jacobs (ed.) Beneficial co-utilization of agricultural, municipal, and industrial by-products. Kluwer Academic Publ., Dordrecht, the Netherlands.
Gilmour, J.T., C.G. Cogger, L.W. Jacobs, S.A. Wilson, G.K. Evanylo, and D.M. Sullivan. 2000. Estimating plant-available nitrogen in biosolids. Project 97-REM-3. Water Environ. Res. Foundation, Alexandria, VA.
Godfree, A., and J. Farrell. 2005. Processes for managing pathogens. J. Environ. Qual. 34:105–113 (this issue).
Hale, R.C., M.J. LaGuardia, E.P. Harvey, M.O. Gaylor, T.M. Mainor, and W.H. Duff. 2001. Persistent pollutants in land-applied sludge. Nature (London) 412:140–141.
Harrison, E.Z., M.B. McBride, and D.R. Bouldin. 1999. Land application of sewage sludges: An appraisal of the US regulations. Int. J. Environ. Pollut. 11:1–36.
Haustein, G.K., T.C. Daniel, D.M. Miller, P.A. Moore, Jr., and R.W. McNew. 2000. Aluminum-containing residuals influence high-phosphorus soils and runoff water quality. J. Environ. Qual. 29:1954–1959.
Interagency Steering Committee on Radiation Standards. 2003. Assessment of radioactivity in sewage sludge: Radiological survey results and analysis. NUREG-1775, EPA832-R-03-002, DOE/EH-0669. ISCORS Tech. Rep. 2003-02. ISCORS, Washington, DC.
Jacobs, L.W., S. Carr, S. Bohm, and S. Stukenberg. 1993. Document long-term experience of biosolids land application programs. Project 91-ISP-4. Water Environ. Res. Foundation, Alexandria, VA.
Jacobs, L.W., G.A. O'Connor, M.A. Overcash, M.J. Zabik, and P. Rygiewicz. 1987. Effects of trace organics in sewage sludges on soil-plant systems and assessing their risk to humans. p. 101–143. *In* A.L. Page, T.G. Logan, and J.A. Ryan (ed.) Land application of sludge. Lewis Publ., Chelsea, MI.
Josan, M., V.D. Nair, W.G. Harris, and D. Herrera. 2005. Associated release of magnesium and phosphorus from active and abandoned dairy soils. J. Environ. Qual. 34:184–191 (this issue).
Karpati, A., and C. Rubin. 1998. Report of a pilot environmental investigation around large poultry operations in Ohio. Centers for Disease Control and Prevention, Atlanta.
Kester, G.B., R.B. Brobst, A. Carpenter, R.L. Chaney, A.L. Rubin, R.A. Schoof, and D.S. Taylor. 2005. Risk characterization, assessment, and management of organic pollutants in beneficially used residual products. J. Environ. Qual. 34:80–90 (this issue).
Koelsch, R. 2005. Evaluating livestock system environmental performance with whole-farm nutrient balance. J. Environ. Qual. 34:149–155 (this issue).
Laine, M.M., and K.S. Jorgensen. 1997. Effective and safe composting of chlorophenol-contaminated soil in pilot scale. Environ. Sci. Technol. 31:371–378.
Laperche, V., and J.M. Bigham. 2002. Quantitative, chemical, and mineralogical characterization of flue gas desulphurization by-products. J. Environ. Qual. 31:979–988.
Logan, T.L., C.L. Henry, J.L. Schnoor, M. Overcash, and D.C. McAvoy. 1999. An assessment of health and environmental risks of trace elements and toxic organics in land-applied municipal solid waste compost. Compost Sci. Util. 7:38–53.
Maguire, R.O., J.T. Sims, S.K. Dentel, F.J. Coale, and J.T. Mah. 2001. Relationships between biosolids treatment process and soil phosphorus availability. J. Environ. Qual. 30:1023–1033.
Mathers, A.C., B.A. Stewart, and J.E. Herring. 1980. Manure and inorganic fertilizer effects on sorghum and sunflower growth on iron-deficient soil. Agron. J. 72:1025–1029.
McCaslin, B.D., J.G. Davis, L. Cihacek, and L.A. Schluter. 1987. Sorghum yield and soil analysis from sludge-amended calcareous iron-deficient soil. Agron. J. 79:204–209.
Mitch, W.A., and D.L. Sedlak. 2004. Characterization and fate of N-nitrosodimethylamine precursors in municipal wastewater treatment plants. Environ. Sci. Technol. 38:1445–1454.
Moss, L.H., E. Epstein, and T.L. Logan. 2002. Evaluating risks and benefits of soil amendments used in agriculture. Rep. 99-PUM-1. Water Environ. Res. Foundation, Alexandria, VA.
Mullin, R. 2004. Cracking the sustainability code. Chemical & Engineering News. 5 January, p. 1.
Nair, V.D., D.A. Graetz, and D.O. Dooley. 2003. Phosphorus release characteristics of manure and manure-impacted soils. Food Agric. Environ. 1:217–223.
National Association of State Universities and Land Grant Colleges. 1973. Proceedings of the Joint Conference on Recycling Municipal Sludges and Effluents on Land, Champaign–Urbana, IL. NASULGC, Washington, DC.
National Research Council. 1983. Risk assessment in the federal government: Managing the process. Natl. Academies Press, Washington, DC.
National Research Council. 2002. Biosolids applied to land: Advancing standards and practices. Natl. Academies Press, Washington, DC.
O'Connor, G.A., R.B. Brobst, R.L. Chaney, R.L. Kincaid, L.R. McDowell, G.M. Pierzynski, A. Rubin, and G.G. Van Riper. 2001. A modified risk assessment to establish molybdenum standards for land application of biosolids. J. Environ. Qual. 30:1490–1507.
O'Connor, G.A., R.L. Chaney, and J.A. Ryan. 1991. Bioavailability to plants of sludge-borne toxic organics. Rev. Environ. Contam. Toxicol. 121:129–155.
Overcash, M.R., R.C. Sims, J.L. Sims, and J.K.C. Nieman. 2005. Beneficial reuse and sustainability: The fate of organic compounds in land-applied waste. J. Environ. Qual. 34:29–41 (this issue).
Page, A.L., T.G. Logan, and J.A. Ryan (ed.) 1987. Land application of sludge. Lewis Publ., Chelsea, MI.
Peters, J.M., and N.T. Basta. 1996. Reduction of excessive bioavailable phosphorus in soils by using municipal and industrial wastes. J. Environ. Qual. 25:1236–1241.
Pierzynski, G.M., and K. Gehl. 2005. Plant nutrient issues for sustainable land application. J. Environ. Qual. 34:18–28 (this issue).
Rusin, P.A., S.L. Maxwell, J.P. Brooks, C.P. Gerba, and I.L. Pepper. 2003. Evidence for the absence of *Staphylococcus aureus* in land applied biosolids. Environ. Sci. Technol. 37:4027–4030.
Ryan, J.A., R.M. Bell, J.M. Davidson, and G.A. O'Connor. 1988. Plant uptake of non-ionic organic chemicals from soils. Chemosphere 17:2299–2323.
Sarret, G., J. Vangronsveld, A. Manceau, M. Musso, J. D'Haen, J.J. Menthonnex, and J.L. Hazemann. 2001. Accumulation forms of Zn and Pb in *Phaseolus vulgaris* in the presence and absence of EDTA. Environ. Sci. Technol. 35:2854–2859.
Schiffman, S., and M. Williams. 2005. Science of odor as a potential health issue. J. Environ. Qual. 34:129–138 (this issue).
Schoof, R.A., and D. Houkal. 2005. The evolving science for chemical risk assessment for land-applied biosolids. J. Environ. Qual. 34:114–121 (this issue).
Sharpley, A.N., T. Daniel, J.T. Sims, J. Lemunyon, R. Stevens, and R. Parry (ed.) 2003. Agricultural phosphorus and eutrophication. 2nd ed. ARS-149 [Online]. Available at www.ars.usda.gov/is/np/Phos&Eutro2/phos&eutrointro2ed.htm (verified 31 Aug. 2004). USDA-ARS, Washington, DC.
Sharpley, A.N., and B. Moyer. 2000. Phosphorus forms in manure and composts and their release during simulated rainfall. J. Environ. Qual. 29:1462–1469.
Shober, A.L., and J.T. Sims. 2003. Phosphorus restrictions for land application of biosolids: Current status and future trends. J. Environ. Qual. 32:1955–1964.
Shore, L.S., D.L. Correll, and P.K. Chakaborty. 1995. Relationship of fertilization with chicken manure and concentrations of estrogens in small streams. p. 155–162. *In* K. Steele (ed.) Animal waste and the land-water interface. CRC Press, Boca Raton, FL.
Sims, J.T. 1995. Characteristics of animal wastes and waste-amended soils: An overview of the agricultural and environmental issues. p. 1–14. *In* K. Steele (ed.) Animal waste and the land-water interface. CRC Press, Boca Raton, FL.

Sims, J.T., R.R. Simard, and B.C. Joern. 1998. Phosphorus loss in agricultural drainage: Historical perspective and current research. J. Environ. Qual. 27:277–293.
Smith, J.E., Jr., P. Millner, W. Jakubowski, N. Goldstein, and R. Rynk (ed.) 2004. Contemporary perspectives on infectious disease agents in sewage sludge and manure. The JG Press, Emmaus, PA.
Stehouwer, R.C., A.M. Wolf, and W.T. Doty. 2000. Chemical monitoring of sewage sludge in Pennsylvania: Variability and application variability. J. Environ. Qual. 29:1686–1695.
Stevens, J.L., and K.C. Jones. 2003. Quantification of PCDD/F concentrations in animal manure and comparison of the effects of the application of cattle manure and sewage sludge on agricultural land on human exposure to PCDD/Fs. Chemosphere 50:1183–1191.
Stevens, J.L., G.L. Northcott, G.A. Stern, G.T. Tomy, and K.C. Jones. 2003. PAHs, PCBs, PCNs, organochlorine pesticides, synthetic musks, and polychlorinated n-alkanes in U.K. sewage sludge: Survey results and implications. Environ. Sci. Technol. 37:462–467.
USEPA. 1990. National sewage sludge survey: Availability of information and data, and anticipated impacts in proposed regulations. Proposal Rule 40 CFR 503. Fed. Regist. 55:47210–47283.
USEPA. 2003a. Standards for the use or disposal of sewage sludge: Decision not to regulate dioxins in land-applied sewage sludge. Fed. Regist. 68:61083–61096.
USEPA. 2003b. Standards for the use or disposal of sewage sludge: Final agency response to the National Research Council report on biosolids applied to land and the results of EPA's review of existing sewage sludge regulations. Fed. Regist. 68:75531–75552.
VanWieringen, L.M., J.H. Harrison, T. Nennich, D.L. Davidson, L. Morgan, S. Chen, M. Bueler, and F. Hoisington. 2005. Manure management effects on grass production, nutritive content, and soil nitrogen for a grass silage–based dairy farm. J. Environ. Qual. 34: 164–173 (this issue).
Washington State Department of Ecology. 1999. Screening survey for metals and dioxins in fertilizer products in Washington State. Ecol. Publ. 99-309. WSDE, Olympia.
Water Environment Research Foundation. 2003. Proceedings of the Biosolids Research Summit, Alexandria, VA. 28–30 July 2003. WERF, Alexandria, VA.
Webber, M.D., and S. Lesage. 1989. Organic contaminants in Canadian municipal sludges. Waste Manage. Res. 7:63–82.
Wilson, S.C., R.E. Alocock, A.P. Stewart, and K.C. Jones. 1997. Persistence of organic contaminants in sewage sludge-amended soil: A field experiment. J. Environ. Qual. 26:1467–1477.
Withers, P.J.A., S.A. Clay, and V.G. Breeze. 2001. Phosphorus transfer following application of fertilizer, manure and sewage sludge. J. Environ. Qual. 30:180–188.
Witte, H., T. Langenohl, and G. Offenbacher. 1988. Investigation of the entry of organic pollutants into soils and plants through the use of sewage sludge in agriculture. Part A. Organic pollutant load in sewage sludge. Part B. Impact of the application of sewage sludge on organic matter contents in soils and plants. Korresp. Abwasser 13:118–136.
Xia, K., A. Bhandari, K. Das, and G. Pillar. 2005. Occurrence and fate of pharmaceuticals and personal care products (PPCPs) in biosolids. J. Environ. Qual. 34:91–104 (this issue).