MASTER COPY

Occasional Report No. 12
ISSN 0112-9902

Proceedings of the Workshop

BEST SOIL MANAGEMENT PRACTICES FOR PRODUCTION

Massey University, Palmerston North, New Zealand

10 - 11 February, 1999

Editors

L D Currie, M J Hedley, D J Horne and P Loganathan

FERTILIZER & LIME RESEARCH CENTRE

Massey University

BEST SOIL MANAGEMENT PRACTICES FOR PRODUCTION

Proceedings of the Workshop held by the

FERTILIZER AND LIME RESEARCH CENTRE

at

Massey University, Palmerston North, New Zealand

10 - 11 February, 1999

Editors

L D Currie, M J Hedley, D J Horne and P Loganathan

The correct citation for these proceedings is

Author(s), 1999. Title of paper. In *Best soil management practices for production.* (Eds L D Currie, M J Hedley, D J Horne and P Loganathan). Occasional report No. 12. Fertilizer and Lime Research Centre, Massey University, Palmerston North. pp

CHALLENGES FOR IDENTIFYING BEST MANAGEMENT PRACTICES – INTEGRATING EMERGING MODERN TECHNOLOGIES AND PHILOSOPHIES

R E Sojka and D R Upchurch
Soil Scientists, USDA-Agricultural Research Service; Northwest Irrigation and Soils Research Laboratory, Kimberly, ID & Cropping Systems Research Laboratory, Lubbock, TX

Abstract
Best management practice. This term is charged with meaning and assumptions. The values affecting the term and its definition are not universal for all farmers, environmental stewards, resource industries, agricultural industries, government bureaus, politicians and the public. How we develop the philosophy governing assessment and adoption of management practices will significantly impact the environment, the public at large and the agricultural community. We submit that natural resources management in general, and particularly management of soil resources must balance three primary considerations–productivity, environmental impact, and sustainability. A given management practice or criterion may not prove beneficial for all three considerations. To obtain the results desired, we must choose and prioritize goals for soil management with as much care as we choose specific practices. The tendency is to adopt a paradigm and do only research confirming the positive aspects of the paradigm. It is important to objectively recognize and weight both the positive and negative contributions of all management alternatives and goals for each of the primary considerations. We explore several traditional and two emerging environmental and agricultural management technologies and philosophies and consider their positive and negative implications for land management at the dawn of the new millennium.

Introduction
Soil science is changing. Of necessity, it is daily becoming more attentive to environmental issues while continuing to carry its entire traditional responsibility of providing new economically sound technologies to raise agricultural productivity. The demands of the evolving global marketplace and increasing complexity of modern science and technology have made each new advancement of even its more narrow traditional role an escalating challenge. The easy problems and discoveries, if there ever were any truly easy ones, given their historical contexts, are behind us. Future technical advances will require greater and greater amounts of energy, work, investment and inspiration. This is not to discount the possibilities for leaps of progress through serendipity and paradigm-altering breakthroughs, but these are not eventualities that we can count on or schedule to meet our needs.

To attain society's goals for a well fed and clothed humanity in a hearty undamaged environment, employing sustainable production practices and strategies, will require a considerable commitment of money and spirit. In addition it will require complete objectivity about our goals, our available resources, the limits of our existing technologies, and the likely limits of our best potential future technologies.

These needs suggest yet another dimension of problem definition. Words like commitment, objectivity, goals, spirit, and paradigm are terms that arise largely from philosophical, economic or even political frameworks. In this context, even "objectivity" doesn't carry the solid connotation of precise scientific exactitude. Objectivity in this context implies diverse possibilities of interpretation that may not be entirely resolved by cold analytical evaluation of data. The natural resource sciences have caught up with medicine, genetics, etc. in the extent to which its research priorities and directions are determined within a context of values and desired social outcomes.

Because the cost of each incremental advancement of science continues to become larger and larger, there are more and more choices that have to be made regarding the allocation and prioritization of resources to fund science. This is especially true in the natural resource sciences. Increasingly, project definition and funding opportunities are shaped in the context of prevailing social and scientific philosophies, rather than by the inventiveness or persuasiveness of scientists or by the unfettered lure of basic discovery. Science funding has largely moved away from the concept of investment in knowledge for potential future uses to the concept of direct payment for solution of immediate problems.

In natural resource sciences and management, our programs and research are governed by three primary considerations: productivity, environmental stewardship, and sustainability. It has not always been so. Environmental and sustainability considerations have only received extensive and intensive attention in recent decades. Productivity includes economic and "survival" considerations ("survival" referring to the requirement of producing output sufficient to meet human needs globally). Environmental stewardship largely implies awareness and limitation of off-site and off-target impacts of management practices and technologies. Sustainability refers largely to on-site environmental impacts and to resource utilization strategies to guarantee continued productivity.

Arguably, the consideration of greatest familiarity and consensus for most soil scientists is productivity. The overwhelming focus on this consideration in the twentieth century has been highly successful if evaluated in terms of food and fiber availability and cost throughout most of the world, as well as positive impacts on human nutrition and life spans (Waggoner, 1994; Avery, 1997a,b; Tribe, 1994). By their estimates 25-30 million square kilometers (equal to the continental area of North America or Africa) have been spared from agricultural development since 1960 by the advances in high technology, high efficiency, high output farming.

That productivity, as a primary focus, has had shortcomings, is borne out by the rise in the consideration of environmental and sustainability concerns, and to a lesser degree by reshaping of the definition of productivity to de-emphasize yield per se and accentuate economic and sustainable yield. The rise in environmental considerations can be attributed partly to the environmental problems caused by the extent of agriculture necessary to meet human needs, including both subsistence-scale and large-scale production farming. Improved analytical methods and monitoring capabilities have made it possible both to assess pollution in the environment and to link specific levels of exposure to health and hygiene problems. However, it could also be argued that there has been a failure of the scientific community to communicate to the public and decision makers the difference between detectability of pollutants and the criticality of threshold exposures. Furthermore, the agricultural sector has largely failed to adequately inform and convince the public and decision makers of the extent to which high-yield high-efficiency agriculture preserves the environment by limiting agriculture's land area requirements and concomitant extent of negative impacts. Real progress in terms of natural resource conservation, agricultural productivity, environmental stewardship, and sustainable land management will require research and decision making that objectively balance all of these considerations.

Managing for high productivity neither automatically benefits nor impairs environmental and sustainability considerations. Neither does simple concern for environmental and sustainable aspects, or abandoning of high technology, high input, high yield farming automatically guarantee positive environmental and sustainable impacts. Few comprehensive analyses of all aspects of soil management have fully weighed all positives and all negatives of all aspects of management for all three considerations. The tendency is to adopt a paradigm and do only research confirming the positive aspects of the paradigm adopted.

In the pages that follow, we present examples of soil management concepts that can have conflicting interpretations based on one or more of the three considerations we have drawn attention to: productivity, environmental impact, sustainability. Our presentation, in the context of a short paper, cannot be regarded as comprehensive. It would take a sizeable volume to consider this topic in adequate depth. Furthermore, we attempt to provide this discussion without weighting it with any interpretation or value assignment of our own. Hopefully these examples will provide a stimulating embarkation point for assessing how we assign values and priorities in setting direction and goals for soil management through formulation of best management practices.

SOIL ORGANIC MATTER (SOM)

Soil organic matter has been shown to provide a multitude of benefits for plant growth. Effects are physical and chemical and both direct and indirect. Its preservation and increase has been a soil management priority of most farming systems, and that rationale is well supported as a productivity consideration, particularly for temperate rainfed agricultural systems. As for most concepts, however, questions that are not asked are seldom addressed. Not surprisingly, there has been little consideration of possible ill consequences of increased SOM in the range of modern farming systems that occur across diverse global settings. This may also be because the heyday of SOM research preceded the more recent focus on environmental issues in agricultural research some twenty years.

Soil organic matter can have negative environmental impacts and crop production impacts. The application requirements of many soil-incorporated pesticides needed to provide pest control increases as SOM content increases (Stevenson, 1972; Ross and Lembi, 1985; Anonymous, 1997; Gaston et al., 1997). As SOM increases from about the 1-3% range to the 3-5% range, the required application rates of soil incorporated pesticide needed for pest control efficacy, commonly rise 20-100%. Clancy (1986) and Hallberg (1987) noted that increased use of synthetic insecticides, fungicides and herbicides increases the probability of human exposure to toxic hazards. This includes risks from manufacture, transport, handling, application, environmental loading, and human exposure via contact in or uptake from the environment. Economic analysis of crop production benefits of SOM, seldom considers the negative environmental quality and human health aspects of the higher pesticide use associated with elevated SOM content.

Among the physical properties directly affected by SOM are its improvement of aggregation and aggregate stability and their contribution to macropore formation. These soil properties are highly beneficial to plant growth, crop production, and micro-ecology through improvement of aeration, root penetration and water infiltration. Macropore formation, however, is the soil property responsible for bypass flow, which allows rapid transmittal of surface-applied contaminants to groundwater (Barriuso et al., 1992; Hassett and Anderson, 1982; Muszkat et al., 1993; Vinten et al., 1983; Flury, 1986; Ghodrati and Jury, 1992; Grochulska and Kladivko, 1994; Shuford et al., 1977, Simpson and Cunnigham, 1982).

Soil organic matter can complex with various soil-applied chemicals. These complexes often result in increased solubility and mobility. Formation of complexes between dissolved SOM and napropamide facilitated the rapid transport of napropamide through a soil column (Nelson et al., 1998). Complexing with soil humic fractions accelerated atrazine transport through soil (Graber et al., 1995; Hayes 1970; Senesi, 1992; Sposito, et al., 1996). Greater DDT and PCB solubility was believed due to complexing with soluble SOM (Chiou et al., 1987). Similar complexing and increased transport was seen in tests involving six herbicides by Mudhun et al. (1986). Organic matter and manure additions have also been associated with increased solubility and movement of phosphorus through soil (Meek et al., 1974, 1979, 1982; Robinson and Sharpley, 1995; Sharpley and Smith, 1995), resulting in phosphorus loss to and contamination of groundwater, or surface waters fed by runoff or springs (Beauchemin et al., 1998; Heckrath et al., 1995; Stamm et al., 1998).

The dark color of SOM lowers soil albedo and results in higher seasonal soil temperatures. In temperate regions this accelerates seed germination, seedling emergence and early crop growth. However, higher soil temperature at midseason can decrease yield and quality of various field and vegetable crops. This is especially true for desert irrigated production or in tropical agriculture.

Colonization and performance of vesicular arbuscular mycorrhiza have been increased by addition of manure or green manure on low organic matter soils, but suppressed by additions to soils with moderate to high organic matter levels (Ellis et al., 1992; Baltruschat and Dehne, 1988; Harinikumar and Bagyaraj, 1989; Brechelt, 1987, 1989; Lambert and Weidensaul, 1991).

EARTHWORMS

Earthworms provide many benefits, as does organic matter, in many soils for crop production, contributing directly to organic matter processing, aggregate formation, macropore formation and nutrient transformations and cycling that are useful to plant nutrition and crop growth. Earthworms, however, also produce negative consequences, most of which are seldom recognized or economically assessed in development of soil management strategies. The macroporosity that results from earthworm contributions to aggregate formation and from their burrows contributes to bypass flow and rapid deep transfer of surface-applied chemicals (Cohen, 1997; Edwards et al., 1989, 1992, 1993; Ehlers, 1975; Hall, et al., 1989, 1991; Isensee et al., 1990; Tyler and Thomas, 1977; Shipitalo et al., 1994; Steenhuis et al., 1990; Trojan and Linden, 1992; Zachmann et al., 1987; Zachmann and Linden, 1989). In rainfed agriculture the increased macroporosity generated by earthworms is generally regarded as beneficially increasing infiltration, thereby helping reduce runoff, and in turn erosion. In furrow irrigated agriculture, however, earthworms are often regarded as problems. They cause a phenomena that many U.S. irrigators refer to as "backing up," which is an abrupt increase in furrow infiltration rate causing the water stream to become insufficient to run the length of the furrow, with the leading edge of the water stream retreating or "backing up" the furrow as the infiltration rate increases. The infiltration increase has been linked to earthworms burrowing to the soil surface to escape suffocation in their flooded burrows (Kemper et al., 1987; Trout et al., 1987; Trout and Johnson, 1989). Field-wide nonuniformity of water application results, severely impacting fertility, leaching, and crop water stress.

The solubility of key plant nutrients increases when earthworms digest organic-matter-rich soil. This is largely regarded as beneficial to plant growth and crop productivity. It can, however, also contribute to runoff water quality degradation (Sharpley and Syers, 1976, 1977; Broussard et al., 1995). Earthworms also promote and accelerate soil nitrogen mineralization (Parkin and Berry, 1994; Blair et al., 1996; Willems et al., 1996). These activities combined with their contribution to soil macropore formation, create negative impacts on groundwater nitrate management, which is further underscored by the common need to use nitrification inhibitors to control mineral availability and limit nitrate leaching to groundwater. Unfortunately, earthworm populations are higher on more fertile, higher organic matter content soils, further exacerbating their negative environmental impacts related to nutrient solubilization.

Earthworms have been shown to be vectors of soil-borne plant diseases (Edwards and Lofty, 1977; Hampson and Coombes, 1989; Hoffman and Purdy, 1964; Khambata and Bhat, 1957; Thornton, 1970; Toyota and Kimura, 1994; Marialigati, 1979; Hutchinson and Kamel, 1956). At short range, the vectoring is direct via ingestion in and through the gut with transport and deposition of organisms above and below ground. At long range, the transport of pathogens is indirect, via birds dropping earthworms and earthworm fragments in flight.

Negative soil property effects have been documented as a result of earthworm activity, depending on species and geographic adaptation. These include increased bulk density and reduced porosity (Alegre et al., 1996; Gilot, 1994; Rose and Wood, 1980). Shrader and Zhang (1997) measured reduction of water-stable aggregation in earthworm casts compared to non-digested aggregates. Pashanasi et al., (1996) found that water retention and sorptivity were reduced by earthworm activity, resulting in impaired soil-plant water relations, increased crop water stress and a 43% reduction in rice yield.

SOIL STRUCTURE

Enhanced aggregation and reduced bulk density and penetration resistance are generally regarded as positive soil attributes. However, again, they must be evaluated in terms of specific processes and contexts. These properties contribute to improved infiltration and aeration and are generally associated with enhanced plant root growth, yield, and quality of numerous crop species (Sojka et al., 1990, 1993a,b, 1997). Again, however, negative consequences of these same soil properties can be demonstrated. We have already alluded to the role of aggregation in macropore formation and bypass flow. Low seed bed bulk density can impair seed germination and stand establishment if pore space distribution is unfavorable for unsaturated water movement to seeds for imbibition, and can limit diffusion and capillary transport of nutrients to roots (Trouse et. al., 1971). Compaction can be managed to resist wind and water erosion under certain circumstances (Larson, 1962; Lyles and Woodruff, 1962). Firm soil also helps reduce wheel slippage and increase traction, lowering horsepower and weight requirements for tillage and other field operations (Gill, 1971), which together conserve fuel and reduce air pollution and carbon dioxide enrichment. Because compaction reduces macropores, it also has been shown to limit bypass flow (Starett et al., 1996).

SOIL MICROBIAL ACTIVITY

High microbial biomass and activity are generally regarded as desirable soil properties frequently associated with positive plant response and crop productivity (Kennedy and Papendick 1995; Kennedy and Smith, 1995; Turco et al., 1994; Yakovchenko et al., 1996). Many of the same physical and chemical properties of soil that favor higher plant response favor microbial growth and function. And many of those functions involve nutrient transformations and cycling activities that benefit crop productivity. Again, however, microorganisms can also result in negative impacts on productivity and environmental considerations. If specific microorganisms are pathogenic or otherwise deleterious to the crop, their contribution to community biomass and function are negative. Examples follow.

Movement of DDT through sand was found to increase eight fold when the sand contained bacteria (Lindqvist and Enfield, 1992). In wet or flooded soils, especially following fresh organic matter incorporation, or when accompanied by high soil temperature, formation of oxygen-restricting surface seals, or compaction, microorganisms compete significantly with plant roots for the dwindling supply of available soil oxygen, accelerating the onset of hypoxia or anoxia. As redox potentials drop, toxic metabolic byproducts or toxic inorganic products of soil chemical reduction result from the direct action of facultative and obligate anaerobes and from their indirect contributions to the drop in soil oxygen diffusion rate (ODR) and redox potential, impairing performance or survivability of most arable crops (Kozlowski, 1984; Glinski and Stepniewski, 1985).

It has been suggested that practices that promote a high soil respiration rate are indicative of good management and environmentally beneficial. Soil respiration is strongly microbially mediated. It is also highly variable, because of the sensitivity of the respiring soil biomass to a wide array of influences. Large respiration rate changes can occur in very short time periods. Influencing factors include soil tillage or other sources of disturbance, season, substrate introduction or removal (root senescence or foliage clipping effects on root exudation), temperature and soil water fluctuation, radiation shifts, fumigation, and application of certain xenobiotics, heavy metals, or various agrichemicals (Bremer et al., 1998; Grahammer, et al., 1991; Lloyd and Taylor, 1994; Fitter et al., 1998; Garcia and Rice, 1994). Alfalfa harvest has been linked in Ohio to increased nitrates appearing in tile drains, which was thought caused by the reduction in plant photosynthate supply to roots, leading to sloughing of nodules and their release of nitrates. Soil respiration regimes can also shift radically between rotation crops, e.g. in the case of soybean and rice rotations in the Southern US., or immediately before and after primary tillage operations, or shifts in weather (Alvarez et al., 1995a,b; Reicosky et al., 1993).

If we evaluate management practices in terms of their ability to sustain high rates of soil respiration, then we must recognize that we are also risking loss of SOM. Respiration is the oxidation of organic sources of carbon to liberate carbon dioxide gas. Thus, elevating soil respiration contradicts two widely accepted environmental and sustainability goals, the maintenance and/or increase of soil organic carbon, and the resulting sequestration of carbon from the atmosphere. Here all three primary considerations of soil management (productivity, environmental impact, and sustainability) pull in opposing directions.

SALINITY AND IRRIGATION INTERACTIONS

Irrigation farmers are forced to reconcile many seemingly contradictory soil management principles. Worldwide, high SOM and low salinity, for examples have as much potential for harm in irrigated land management as they do for good and vice versa; moderately saline, low organic matter content irrigated soils are routinely managed for high productivity (Sojka, 1996, 1998; Bucks et al., 1990). Specificly, Natrustolls or other soils with natric horizons (Solonetzic soils) compromise a range of soils with low salinity and high organic matter, but which are nearly incapable of supporting higher plant life. This is because the organic matter and clays are dispersed by the high ratio of sodium on the exchange complex of the soil and in the soil water. This dispersion destroys structure, sealing pores and limiting drainage and restricting air entry. The opposite extreme explains how arid zone soils can be managed at their high levels of productivity. Most arid-zone soils have low SOM contents, low earthworm populations, considerable salinity and, on average, produce twice the yield and three times the area-based crop value of rainfed agriculture (Kendall and Pimentel 1994; Bucks et al. 1990). The seeming contradiction is possible because of the principles of water management specific to arid zone irrigation. Aggregate stability, porosity, hydraulic conductivity and aeration of low organic matter irrigated soils are impaired by distilled water or sodium (which expand the charged double layer in surface active water, causing particle dispersion) but are improved if irrigation water delivers an adequate balance of divalent cations (eg. calcium salts, which collapse the double layer and promote particle attraction) and allows for leaching (Rhoades, 1972, 1998). Thus, given these soil management considerations and the range of crop salt-sensitivity, soil salinity alone is an unreliable indicator of soil productivity. Soil managers must know the crop to be grown, the nature of the soil salinity (exchangeable sodium percentage--ESP, boron content, etc.) and the nature (sodium adsorption ratio--SAR and electrical conductivity--EC), amount, timing and evaporation path (positional salt deposition on irrigated beds) of irrigation water, as well as the achievable leaching fraction (Rhoades, 1972, 1998).

Managing for SOM content as a high priority in hot arid zone irrigated soils does not seem practical for desert soils. Meek et al. (1982) showed that Holtville sc (Typic Torrifluvents) in Brawley, California, retained only a mean of 0.6% increase in soil organic matter over the unamended 1.0% OM control, five years after a three-year accumulated application of 360 to 540 t/ha manure. While some soil and crop properties benefitted, the logistics and cost of such high application rates are unacceptable, as is the potential for introducing salt imbalances from the manuring. Furthermore, the rapid rate of SOM oxidation prevents long term benefit under these conditions. Thus under these circumstances the management considerations for productivity, environmental impact, and sustainability could conceivably all be negatively impacted, given transport and fuel consumption and costs and air pollution impacts.

POLLUTION VS. FILTRATION

Sims et al. (1997) proposed a non-polluted criteria for assessment of the soil sustainability consideration that they referred to as the *clean* state of soil. However, for other than a discrete list of xenobiotic substances, "pure soil" is difficult to define. Naturally occurring toxins and heavy metals are common at detectable levels in soils and parent materials, and in managed soils, both naturally occurring and anthropogenic toxic substances often accumulate.

One of many legitimate uses and natural roles of soil in global ecology is its function as a filter. Soils can sequester large amounts of pollutants before threatening biological organisms or the healthiness of food (Cook and Hendershot, 1996). Soil managed as a filter media requires sink capacity for toxins, i.e., the ability to be *unclean*. In other words sustainability of soil as a filter media means the ability to maintain sink capacity and be polluted without causing off-site environmental impacts. Some of these reasoning difficulties also carry over to agricultural settings. Making a soil *unclean* by adding toxic herbicides and pesticides improves soil productivity by suppressing target organisms while raising "pollutant" concentrations. However, if the pollutants are quick to degrade and have no lasting harmful effects then we should be cautious about inconsistency in too easily applying a pollution rationale as a basis for limiting their use.

NEW TECHNOLOGIES

Many new technologies have become available to soil management in recent years. They vary in cost and complexity and some carry the potential to change the analysis and prioritization of decisions affecting many aspects of management. We present two familiar examples to indicate the way in which many comfortable assumptions about soil management considerations may need to be rethought.

The ARS laboratory in Kimberly, Idaho has had great success since 1991 placing small amounts of polyacrylamide (PAM), a synthetic organic polymer, in irrigation water to halt erosion and increase infiltration compared to untreated water (Lentz et al., 1992, 1998; Lentz and Sojka, 1994; Sojka et al., 1998a,b). PAM is a water soluble commercial flocculent and soil structural stabilizer. Space does not allow full explanation of the technology in this paper (see the above citations for details), but suffice it to say that several aspects of the new technology challenge long held comfortable paradigms. To begin with, using PAM in this way amounts to placing a chemical in water in order to clean it up. We have often had to expend considerable effort to overcome the uneasiness of environmental regulators with this fact. Next we have told irrigators that to take best advantage of the technology to improve field irrigation uniformity they should double or even triple their furrow inflow rates to shorten stream advance times across fields (reduce infiltration opportunity time differences). This is possible because treated water is nearly non-erosive, yet several important aspects of furrow irrigated field design and water management have evolved from flow management considerations to prevent erosion. Also, recent analysis has shown that adding a few kilograms per hectare annually to fields in this manner can improve surface aggregate stability more dramatically than is often seen with addition of tons of manure or compost or from substantially raising SOM content on Portneuf soils. This should shift the focus of manure and compost application for many furrow irrigators from consideration of physical benefits to better understanding the impacts of manure or compost on nutrient cycling. On the other hand, recent findings have shown that PAM also greatly reduces the transfer of microorganisms in irrigation return flows, carrying the potential to eliminate or at least greatly reduce a major public health concern about use of animal waste on surface irrigated fields contributing return flows to public waters.

Wind induced soil erosion has multiple impacts on crop productivity, environmental stewardship, and long-term sustainability of agricultural productivity. Erosion by wind tends to remove the finest soil particles, primarily clay sized, which are the source of most of the cation exchange capacity. As these particles are removed, the ability of the affected soil to retain soil nutrients is reduced, as is the water holding capacity of the near surface soil. Movement of the soil near the soil surface abrades plants, reducing vigor and increasing susceptibility to pathogens. Small particles entrained in the air are transported over large distances, inducing offsite effects, including damaging equipment, contaminating surface water, and imperiling human and animal health. Recent research has been conducted in Lubbock, Texas, to quantify the capacity of soils to produce dust in the PM10 size-range (aerodynamic diameter less than 10 microns), as an indicator of the susceptibility of the soil to erosion by wind and its contribution to suspended particulates (Zobeck and Gill, 1999). Clearly a low potential for emitting PM10 sized particles would be a positive characteristic of a soil in a susceptible region. However, frequently the reduced dust potential is associated with increased sand sized particles and crops grown on these soils are exposed to increased risk to abrasion by saltating sand grains. In contrast, a soil determined to have a high potential for producing PM10 dust may also be erodible and removed from production. However, soils with the highest potential to emit fine dust often have the highest potential crop productivity. Fine particles provide a reservoir to hold plant nutrients and are the primary mechanism for increasing aggregation of the soil. In addition, soil aggregation is a major factor in reducing the susceptibility of soil to erosion by wind, particularly when there is insufficient crop residue. The very characteristic that indicates an environmental risk--fine particles--enhances the nutrient and water holding capacity, thereby providing increased productivity.

CONCLUSIONS

By one estimate, global agricultural production must rise over 2% per year between now and 2025 to meet the needs of rising global population (Waggoner, 1994). This assumes we wish to preserve natural lands and provide our needs mainly from existing farmlands. Paarlberg (1994) estimated that more food will have to be grown by the human race in the first generation of the new millennium than was grown in the preceding 10,000 years of farming. Crosson (1997) who analyzed global soil productivity loss concluded that accumulated productivity losses to date have actually been quite limited and that our needs for the future should continue to focus not merely on conservation and sustainability but especially on continuing to develop new technologies aimed at increasing agricultural productivity and yields.

Designating best management practices for agriculture is an activity that will have to include a conscious assessment of all three principle natural resource considerations: productivity, environmental impact and sustainability. Even with great clarity of reasoning and oracular ability to perceive society's future needs, the weighting of these considerations in suggesting best management practices is a difficult task.

It is particularly important that designation of best management practices do not overly credit positive attributes or fail to credit negative attributes to systems components. This is particularly important because so many of our perceptions of the contribution (positive or negative) of various soil attributes have been formulated primarily from an edaphological perspective but are now being used in new environmental and sustainability contexts for which not all system effects have been considered or accurately weighted.

As scientists, we should recognize that many of the principles that we think we know about natural resource management (especially soil management) have originated from a long history of focusing almost exclusively on productivity. Benefits of practices and specific soil properties learned from productivity considerations may not transfer directly to the additional considerations of environmental impact or sustainability if a full list of positives and negatives is considered for each specific attribute. Conversely, elements of modern high efficiency agriculture should not be dismissed out of hand as environmentally unsound or be considered to contribute only negative environmental impacts, when indeed, the increases of productivity have substantial environmental benefit, because of the freedom to limit the extent of agriculture necessary to support human needs.

Given management practices and criteria may not prove beneficial for all three primary considerations of soil management at all times or under all circumstances. We must choose goals for soil management with as much care as we choose specific practices to obtain desired results. Choosing these goals ultimately depends on the societal values prioritized and the rewards and disincentives used to encourage and reinforce the attainment of the goals, or that affect agricultural systems indirectly through marketplace or logistical influences. Regardless of the desired outcomes and values acted upon, soil scientists will increasingly need to recognize and objectively weight both the positive and negative contribution of management alternatives to all three primary considerations of soil management.

LITERATURE CITED

Alegre, J.C., B. Pashanasi, and P. Lavelle. 1996. Dynamics of soil physical properties in Amazonian agroecosystems inoculated with earthworms. Soil Sci. Soc. Am. J. 60:1522-1529.

Alvarez, R., O.J. Santanatoglia, P.E. Daniel, and R. Garcia. 1995a. Respiration and specific activity of soil microbial biomass under conventional and reduced tillage. Pesq. Agropec. Bras. 30:701-709.

Alvarez, R., O.J. Santanatoglia, and R. Garcia. 1995b. Effect of temperature on soil microbial biomass and its metabolic quotient in situ under different tillage systems. Biol. Fertil. Soils. 19:227-230.

Anonymous. 1997. Crop Protection Reference, 13th edition. C & P Press, Inc. New York, NY. 2230 pages.

Avery, D.T. 1997a. Saving the Planet with Pesticides and Plastic. Hudson Institute. Indianapolis, IN.

Avery, D.T. 1997b. Avery Testifies Before Senate Ag Committee. Global Food Quarterly. 20:1-2,7-8.

Baltruschat, H., and H.W. Dehne. 1988. The occurrence of vesicular-arbuscular mycorrhiza in agro-ecosystems. I. Influence of nitrogen fertilization and green manure in continuous monoculture and in crop rotation on the inoculum potential of winter wheat. Plant Soil. 107:270-284.

Barriuso, E., U. Baer, and R. Calvet. 1992. Dissolved organic matter and adsorption-desorption of dimefuron, atrazine and carbetamide by soils. J. Environ. Qual. 21:359-367.

Beauchemin, S., R.R. Simard, and D. Cluis. 1998. Forms and concentration of phosphorus in drainage water of twenty-seven tile-drained soils. J. Environ. Qual. 27:721-728.

Blair, J.M., M.F. Allen, R.W. Parmelee, D.A. McCartney, and B.A. Stinner. 1996. Changes in soil N pools in response to earthworm population manipulations in agroecosystems with different N sources. Soil Biol. Biochem. 29:361-367.

Brechelt, A. 1987. Wirkung verschiedener organischer Dungemittel auf die effizienz der va-mykorrhiza. J. Agron. And Crop Sci. 158:280-286.

Brechelt, A. 1989. Effect of different organic manures on the efficiency of VA mycorrhiza. Agric. Ecosys. and Environ. 29:55-58.

Bremer, D.J., J.M. Ham, C.E. Owensby, and A.K. Knapp. 1998. Response of soil respiration to clipping and grazing in a tallgrass prairie. J. Environ. Qual. 27:1539-1548.

Broussard, M., P. Lavelle, and A.V. Spain. 1995. Digestion of a Vertisol by an endogeic earthworm (*Polypheretima elongata*, Megascolecidae) increases soil phosphate extractability. Eur. J. Soil Biol. (Vol?page?).

Bucks, D.A., T.W. Sammis, and G.L. Dickey. 1990. Irrigation for arid areas. pp. 499-548. *IN*: Management of Farm Irrigation Systems. G.J. Hoffman, T.A. Howell, and K.H. Solomon (eds.). Am. Soc. Ag. Eng., St. Joseph, MI.

Clancy, K.L. 1986. The role of sustainable agriculture in improving the safety and quality of the food supply. Amer. J. Altern. Agric. 1:11-18.

Chiou, C.T., D.E. Kile, T.I. Brinton, R.L. Malcolm, and J.A. Leenheer. 1987. A comparison of water solubility enhancements of organic solutes by aquatic humic materials and commercial humic acids. Environ. Sci. Technol. 21:1231-1234.

Cohen, S. 1997. Macropores in turfgrass soil columns. Ground Water Monitoring and Remediation. 17(4):59-62.

Cook, N. and W.H. Hendershot. 1996. The problem of establishing ecologically based soil quality criteria: The case of lead. Can. J. Soil Sci. 76:335-342.

Crosson, P. 1997. Will erosion threaten agricultural productivity? Environment 39:4-9, 29-31.

Edwards, C.A., and Lofty, J.R. 1977. Biology of Earthworms. 2nd ed. Chapman and Hall, London. 333p.

Edwards, W.M., M.J. Shipitalo, L.B. Owens, and W.A. Dick. 1993. Factors affecting preferential flow of water and atrazine through earthworm burrows under continuous no-till corn. J. Environ. Qual. 22:453-457.

Edwards, W.M., M.J. Shipitalo, L.B. Owens, and L.D. Norton. 1989. Water and nitrate movement in earthworm burrows within long-term no-till cornfields. J. Soil Water Conserv. 44:240-243.

Edwards, W.M., M.J. Shipitalo, S.J. Traina, C.A. Edwards, and L.B. Owens. 1992. Role of *Lumbricus terrestris* (L.) Burrows on the quality of infiltrating water. Soil Biol. Biochem. 24:1555-1561.

Ehlers, W. 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soil. Soil Sci. 119:242-249.

Ellis, J.R., W. Roder and S.C. Mason. 1992. Grain sorghum-soybean rotation and fertilization influence in vesicular-arbuscular mycorrhizal fungi. Soil Sci. Soc. Am. J. 56:789-794.

Fitter, A.H., J.D. Graves, G.K. Self, T.K. Brown, D.S. Bogie, and K. Taylor. 1998. Root production, turnover, and respiration under two grassland types along an altitudinal gradient: Influence of temperature and solar radiation. Oecologia 114:20-30.

Flury, M. 1996. Experimental evidence of transport of pesticides through field soils–a review. J. Environ. Qual. 25:25-45.

Garcia, F.O., and C.W. Rice. 1994. Microbial biomass dynamics in tallgrass prairie. Soil Sci. Soc. Am. J. 58:816-823.

Gaston, L.A., K.N. Reddy, and M.A. Locke. 1997. Relationship of spatially variable soil properties to herbicide efficacy. Agron. Abstr. page 336.

Ghodrati, M., and W.A. Jury. 1992. A field study of the effect of soil structure and irrigation method on preferential flow of pesticides in unsaturated soil. J. Contam. Hydrol. 11:101-120.

Gill, W.R. 1971. Economic assessment of soil compaction. Pages 431-458. IN (K.K. Barnes et al., eds) Compaction of Agricultural Soils. Am. Soc. Ag. Eng., St. Joseph, MI

Gilot, C. 1994. Effets de l'introduction du ver geophage tropical *Millsonia anomala* Omodeo en systemes cultives sur les caracteristiques des sols et la production vegetale en Moyenne Cote d'Ivoire. Ph.D. diss. Univ. Paris VI/Institu National Agronomique de Paris-Gringon.

Glinski, J., and W. Speniewski. 1985. Soil Aeration and Its Role for Plants. CRC Press. Boca Raton, 229 pages.

Graber, E.R., A. Gerstl, E. Fischer, and U. Mingelgrin. 1995. Enhanced transport of atrazine under irrigation with effluent. Soil Sci. Soc. Am. J. 59:1513-15-19.

Grahammer, K., M.D. Jawson, and J. Skopp. 1991. Day and night soil respiration from a grassland. Soil Biol. Biochem. 23:(1):77-81.

Grolchulska, J., and E.J. Kladivko. 1994. A two-region model of preferential flow of chemicals using a transfer function approach. J. Environ. Qual. 23:498-507.

Hall, J.K., R.O. Mumma, and D.W. Watts. 1991. Leaching and runoff losses of herbicides in a tilled and untilled field. Agric. Ecosyst. Environ. 37:303-314.

Hall, J.K., M.R. Murray, and N.L. Hartwig. 1989. Herbicide leaching and distribution in tilled and untilled soil. J. Environ. Qual. 18:439-445.

Hallberg, G.R. 1987. Agricultural chemicals in ground water: extent and implications. Amer. J. Altern. Agric. 2:3-15.

Hampson, M.C., and J.W. Coombes. 1989. Pathogenesis of *Synchytrium endobioticum* VII. Earthworms as vectors of wart disease of potato. Plant and Soil 116:147-150.

Harinikumar, K.M., and D.J. Bagyaraj. 1989. Effect of cropping sequence, fertilizers and farmyard manure on vesicular-arbuscular mycorrhizal fungi in different crops over three consecutive seasons. Biol. Fertil. Soils 7:173-175.

Hassett, J.P., and M.A. Anderson. 1982. Effects of dissolved organic matter on adsorption of hydrophobic organic compounds by river- and sewage-bourne particles. Water Res. 16:681-686.

Hayes, M.H.B. 1970. Adsorption of triazine herbicides on soil organic matter, including a short review on soil organic matter chemistry. Res. Rev. 32:131-174.

Heckrath, G., P.C. Brookes, P.R. Poulton, and K.W.T. Goulding. 1995. Phosphorus leaching from soils containing different phosphorous concentrations in the Broadbalk experiment. J. Envron. Qual. 24:904-910.

Hoffman, J.A., and L.H. Purdy. 1964. Germination of dwarf bunt teliospores after ingestion by earthworms. Phytopathology. 54:878-879.

Hutchison, S.A., and M. Kamel. 1956. The effect of earthworms on the dispersal of soil fungi. J. Soil Sci. 7:213-218.

Isensee, A.R., R.G. Nash, and C.S. Helling. 1990. Effect of conventional and no-tillage on pesticide leaching to shallow groundwater. J. Envir. Qual. 19:434-440.

Kemper, W. D., T. J. Trout, Antone Segeren, and Murray Bullock. 1987. Worms and water. J. Soil & Water Cons. 42(6):401-404.

Kendall, H.W., and D. Pimentel. 1994. Constraints on the expansion of the global food supply. Ambio 23:198-205.

Kennedy, A.C., and R.I. Papendick. 1995. Microbial Characteristics of soil quality. J. Soil Water Conserv. 50:243-248.

Kennedy, A.C., and K.L. Smith. 1995. Soil microbial diversity and the sustainability of agricultural soils. Pages 75-86. IN (H.P. Collins et al., eds.) The Significance and Regulation of Soil Biodiverity. Kluwer Academic Publishers, Amsterdam.

Khambata, S.R. and J.V. Bhat. 1957. A contribution to the study of the intestinal microflora of Indian earthworms. Arch. Mikrobiol. 28:69-80.

Kozlowski, T.T (ed). 1984. Flooding and Plant Growth. Academic Press, Inc., Orlando. 356 pages.

Lambert, D.H. and T.C. Weidensaul. 1991. Elemental uptake by mycorrhizal soybean from sewage-sludge-treated soil. Soil Sci. Soc. Am. J. 55:393-398.

Larson, W.E. 1962. Tillage requirements for corn. J. Soil Water Conserv. 17(1):3-7.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56:1926-1932.

Lentz, R.D., and R.E. Sojka. 1994. Field results using polyacrylamide to manage furrow erosion and infiltration. Soil Sci. 158:274-282.

Lentz, R.D., R.E. Sojka, and C.W. Robbins. 1998. Reducing phosphorus losses from surface irrigated fields: Emerging polyacrylamide technology. J. Environ. Qual. 27:305-312.

Lindqvist, R., and C.G. Enfield. 1992. Biosorption of dichlorodiphenyltrichloroethane and hexachlorobenzene in groundwater and its implication for facilitated transport. Appl. Environ. Microbiol. 58:2211-2218.

Lloyd, J., and J.A. Taylor. 1994. On the temperature dependence of soil respiration. Funct. Ecol. 8:315-323.

Lyles, L., and N.P. Woodruff. 1962. How moisture and tillage effect soil cloddiness for wind erosion control. Agric. Eng. 43:150-153, 159.

Marialigeti, K. 1979. On the community-structure of the gut-microbiota of *Eisenia lucens* (Annelida, Oligochaeta). Pedobiologia 19:213-220.

Meek, B., L. Graham, and T. Donovan. 1982. Long-term effects of manure on soil nitrogen, phosphorus, potassium, sodium, organic matter, and water infiltration. Soil Sci. Soc. Am. J. 46:1014-1019.

Meek, B.D., L.E. Graham, T.J. Donovan, and K.S. Mayberry. 1979. Phosphorus availability in a calcareous soil after high loading rates of animal manure. Soil Sci. Soc. Am. J. 43:741-744.

Meek, B.D., A.J. MacKenzie, T.J. Donovan, and W.F. Spencer. 1974. The effect of large application of manure on movement of nitrate and carbon in an irrigated desert soil. J. Environ. Qual. 3:253-258.

Mudhun, Y.A., J.L. Young, and V.H. Freed. 1986. Binding of herbicides by water-soluble organic materials from soil. J. Environ. Qual. 15:64-68.

Muszkat, L., D. Raucher, M. Margaritz, D. Ronen, and A.J. Amiel. 1993. Unsaturated zone and ground-water contamination by organic pollutants in a sewage-effluent-irrigated site. Groundwater 31:556-565.

Nelson, S.D., J. Letey, W.J. Farmer, C.F. Williams, and M. Ben-Hur. 1998. Facilitated transport of napropamide by dissolved organic matter in sewage sludge amended soil. J. Environ. Qual. (IN PRESS, Sept. '98).

Paarlberg, R.L. 1994. The politics of agricultural resource abuse. Environment 36:7-41.

Parkin, T.B., and E.C. Berry. 1994. Nitrogen transformations associated with earthworm casts. Soil Biol. Biochem. 26:1233-1238.

Pashanasi, B., P. Lavelle, and J. Alegre. 1996. Effect of inoculation with the endogeic earthworm *Pontoscolex corethrurus* on soil chemical characteristics and plant growth in a low-input agricultural system of Peruvian Amazonia. Soil Biol. Biochem. 28:(6)801-810.

Reicosky, D.C., and M.J. Lindstrom. 1993. Fall tillage method: Effect on short-term carbon dioxide flux from soil.

Rhoades, J.D. 1972. Quality of water for irrigation. Soil Sci. 113:277-284.

Rhoades, J.D. 1998. Use of saline and brackish waters for irrigation: Implications and role in increasing food production, conserving water, sustaining irrigation and controlling soil and water degradation. pp. 261-304. IN Ragab and G. Pearce (eds.), Proceedings of the International Workshop on "The Use of Saline and Brackish Water for Irrigation," July 23-24, 1998, Bali Indonesia, International Commission on Irrigation and Drainage, Salt Lake City, UT.

Robinson, J.S., and A.N. Sharpley. 1995. Release of nitrogen and phosphorus from poultry litter. J. Envir. Qual. 24:62-67.

Rose, C.J., and A.W. Wood. 1980. Some environmental factors affecting earthworm population and sweet potato production in the Tari Basin, Papua New Guinea highlands. Pap. New Guin. Agric. J. 31:1-13.

Ross, M.A., and C.A. Lembi. 1985. Applied Weed Science. Macmillan and Company, New York.

Senesi, N. 1992. Binding mechanisms of pesticides to soil humic substances. Sci. Total Environ. 123/124:63-76.

Sharpley, A.N., and S.J. Smith. 1995. Nitrogen and phosphorus forms in soils receiving manure. Soil Sci. 159:253-258.

Sharpley, A.N., and J.K. Syers. 1976. Potential role of earthworm casts for the phosphorus enrichment of run-off waters. Soil Biol. Biochem. 8:341-346.

Sharpley, A.N., and J.K. Syers. 1977. Seasonal variation in casting activity and in the amounts and release to solution of phosphorus forms in earthworms casts. Soil Biol. Biochem. 9:227-231.

Shipitalo, M.J., W.M. Edwards, and C.E. Redmond. 1994. Comparison of water movement and quality in earthworm burrows and pan lysimeters. J. Envir. Qual. 23:1345-1351.

Shrader, S., and H. Zhang. 1997. Earthworm casting: stabilization or destabilization of soil structure? Soil Biol. Biochem. 29:469-475.

Shuford, J.W., D.D. Fritton, and D.E. Baker. 1977. Nitrate-Nitrogen and chloride movement through undisturbed field soil. J. Envir. Qual. 6:255-259.

Simpson, T.W., and R.L. Cunnigham. 1982. The occurrence of flow channels in soils. J. Envir. Qual. 11:29-30.

Sims, J.T., S.D. Cunningham and M.E. Sumner. 1997. Assessing soil quality for environmental purposes: Roles and challenges for soil scientists. J. Environ. Qual. 26:20-25.

Sojka, R.E., W.J. Busscher, D.T. Gooden, and W.H. Morrison. 1990. Subsoiling for sunflower production in the Southeast Coastal Plains. Soil Sci. Soc. Am. J. 54:1107-1112.

Sojka, R.E., D.J. Horne, C.W. Ross, and C.J. Baker. 1997. Subsoiling and surface tillage effects on soil physical properties and forage oat stand and yield. Soil & Tillage Research. 40:125-144.

Sojka, R.E., R.D. Lentz, C.W. Ross, T.J. Trout, D.L. Bjorneberg, and J.K. Aase. 1998a. Polyacrylamide effects on infiltration in irrigated agriculture. J. Soil Water Conserv. 53(4)325-331.

Sojka, R.E., R.D. Lentz, and D.T. Westermann. 1998b. Water and erosion management with multiple applications of polyacrylamide in furrow irrigation. Soil Sci. Soc. Am. J. 62:1672-1680.

Sojka, R.E., D.T. Westermann, M.J. Brown and B.D. Meek. 1993a. Zone-subsoiling effects on infiltration, runoff, erosion, and yields of furrow-irrigated potatoes. Soil & Tillage Research. 25:351-368.

Sojka, R.E., D.T. Westermann, D.C. Kincaid, I.R. McCann, J.L. Halderson, and M. Thornton. 1993b. Zone-subsoiling effects on potato yield and grade. Am. Pot. J. 70:475-484.

Sojka, R.E. 1996. Irrigation. *IN*: 1997 Yearbook of Science and Technology. Sybil Parker (ed). McGraw Hill, New York, pages 258-260.

Sojka, R.E. 1998. Understanding and Managing Irrigation-Induced Erosion, pages 21-37. *IN*: F.J. Pierce and W.W. Frye (eds.) Advances in Soil and Water Conservation. Sleeping Bear Press, Ann Arbor Press, Chelsea, MI.

Sposito, G., L. Martin-Neto, and A. Yang. 1996. Atrazine complexation by soil humic acids. J. Environ. Qual. 25:1203-1209.

Stamm, C., H. Fluhler, R. Gachter, J. Leuenberger, and H. Wunderll. 1998. Preferential transport in drained grassland soils. J. Environ. Qual. 27:515-522.

Starrett, S.K., N.E. Christians, and T.A. Austin. 1996. Comparing dispersivities and soil chloride concentrations of turfgrass-covered undisturbed and disturbed soil columns. J. of Hydrol. 180:21-29.

Steenhuis, T.S., W. Staubitz, M.S. Andreini, J. Surface, T.L. Richard, R. Paulsen, N.B. Pickering, J.R. Hagerman, and L.D. Geohring. 1990. Preferential movement of pesticides and tracers in agricultural soils. J. Irrig. Drain. Eng. 116:50-66.

Stevenson, F.J. 1972. Organic matter reactions involving herbicides in soils. J. Environ. Qual. 1:333-343.

Thornton, M.L. 1970. Transport of soil-dwelling aquatic phycomycetes by earthworms. Trans. Br. Mycol. Soc. 55:391-397.

Toyota, K., and M. Kimura. 1994. Earthworms disseminate a soil-borne plant pathogen, Fusarium oxysporum f. sp. Raphani. Biol Fertil. Soils. 18:32-36.

Tribe, D.E. 1994. Feeding and Greening the World--The Role of International Agricultural Research. CAB International, Published by Biddles, Ltd., Guildford, UK.

Trojan, M.D., and D.R. Linden. 1992. Microrelief and rainfall effects on water and solute movement in earthworm burrows. Soil Sci. Soc. Am. J. 56:727-733.

Trouse, A.C.Jr., D.H. Parish, and H.M. Taylor. 1971. Soil conditions as they affect plant establishment, root development and yield. Pages 225-314. IN (K.K. Barnes et al., eds) Compaction of Agricultural Soils. Am. Soc. Ag. Eng., St. Joseph, MI.

Trout, T.J., and G.S. Johnson. 1989. Earthworms and furrow irrigation infiltration. Trans. of the ASAE 32(5):1594-1598.

Trout, Thomas J., W. D. Kemper, and G. S. Johnson. 1987. Earthworms cause furrow infiltration increase. Proc. of the Intl. Conf. on Infiltration Development and Application, Jan 6-9, Honolulu, Hawaii. Edited by Yu-Si Fok, Water Resources Res. Centr., Univ. of Hawaii, Honolulu, pages 398-406.

Turco, R.F., A.C. Kennedy, M.D. Jawson. 1994. Microbial indicators of soil quality. *IN:* Doran, J.W. et al. (eds.) Defining soil quality for a sustainable environment, pages 73-90. SSSA Spec. Publ. 35. Madison, WI.

Tyler, D.D., and G.W. Thomas. 1977. Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. J. Envir. Qual. 6:63-66.

Vinten, A.J.A., B. Yaron, and P.H. Nye. 1983. Vertical transport of pesticides into soil when adsorbed on suspended particles. J. Agric. Food Chem. 31-662-664.

Waggoner, P.E. 1994. How much land can ten billion people spare for nature? Council on Agricultural Science and Technology Report 121. 64 pages. Ames, Iowa.

Willems, J.J.G.M., J.C.Y. Marinissen, and J. Blair. 1996. Effects of earthworms on nitrogen mineralization. Biol. Fert. Soils. 23:57-63.

Yakovchenko, V., L.J. Sikora, and D.D. Kaufman. 1996. A biologically based indicator of soil quality. Biol. Fertil. Soils. 21:245-251.

Zachmann, J.E., and D.R. Linden. 1989. Earthworm effects on corn residue breakdown and infiltration. Soil Sci. Soc. Am. J. 53:1846-1849.

Zachmann, J.E., D.R. Linden, and C.E. Clapp. 1987. Macroporous infiltration and redistribution as affected by earthworms, tillage, and residue. Soil Sci. Soc. Am. J. 51:1580-1586.

Zobeck, T. M., T. E. Gill, J. E. Stout, M. L. Zhang, A. C. Kennedy, and J.M. Gregory. 1999. Analysis of laboratory-generated dust suspensions derived from soils and roads. Paper No.97-2030. American Society of Agricultural Engineers. St. Joseph, MI. 1997.