MICROBIAL RESPIRATION AS AN INDEX OF SOIL AERATION IN COMPACTED AND SEWAGE SLUDGE AMENDED SOILS

by

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ABSTRACT

The use of liquid sewage sludge on agricultural soils may improve productivity, but cause compaction due to an application procedure requiring multiple passes with heavy machinery. The movement of water through the soil profiles was used as an index indicating a greater degree of compaction in soils amended with high amounts of sewage sludge vs. low amounts or inorganic fertilizer.

Laboratory studies developed a method to utilize CO_2 evolution from microbial respiration as an index of soil aeration. Samples of Pima clay loam soil of varying moisture levels were amended with inorganic fertilizer or sewage sludge and compacted to several bulk densities. Aeration restricted microbial respiration at 1.6 Mg m^{-3} bulk density and 0.24 g g^{-1} , and 1.4 Mg m^{-3} bulk density and 0.26 g g^{-1} moisture, with no variation due to soil amendments. Respiration rates increased in a compacted sewage sludge amended soil, after an incubation period, indicating an improvement in soil structure due to the sludge.

INTRODUCTION

Organic waste products such as manures and compost have traditionally been used as soil amendments to improve soil physical properties and to supply nitrogen and other essential nutrients to agricultural soils. With the advent of inorganic chemical fertilizers, which are more cost effective and can supply all essential nutrients, the use of organic matter as fertilizer declined in production agriculture. In recent years, increased costs of inorganic chemical fertilizers, the need to dispose of organic waste products, and declining soil productivity due to poor soil structure have caused a renewed interest in the use of manures, composts and other organic waste products as fertilizers.

The use of organic matter as a soil amendment has an impact on several aspects of soil productivity. The addition of large quantities of organic matter to soils can decrease the soil bulk density, improve soil aeration and water holding capacity and improve the structural stability of the soil.

Soil chemical and biological properties are also enhanced by organic matter amendments. Organic matter not only supplies the macronutrients essential to plant growth, but many of the micronutrients not provided by standard chemical fertilizers. Nutrient availability is further enhanced by the ability of organic matter to increase the cation exchange capacity of the soil and to function as a chelate for micronutrients. Microbial activity is also stimulated by the carbon source and growth factors provided in organic matter.

The interest in organic matter amendments is further encouraged by the need to dispose of increasing quantities of organic waste products accumulating in our modern society. Of particular interest are the large quantities of liquid sewage sludge generated by waste water treatment plants. Traditional disposal methods for this sludge include dumping into the oceans, incineration, and depositing in land fills. Such practices can be environmentally hazardous and are of no constructive value (Epstein, 1975).

A better understanding is needed of the effects of sewage sludge as a soil amendment, and the optimal application rates. Maximum application rates are desirable to provide an economically efficient method of disposal, but large quantities of liquid sewage sludge are difficult to apply to agricultural soils without causing compaction of the soil. Anaerobically digested liquid sewage sludge is typically less than 5% solids, thus soils are well saturated after one sludge application due to the high water content of the sludge. Fine-textured soils tend to retain more water than coarse-textured soils and moist soils are more readily compacted under the stress of heavy equipment than drier soils. Since the application of high sludge rates requires several passes over the field with heavy equipment, compaction can become a serious problem on fine-textured soils if not allowed to dry sufficiently between application times. Partially dried sewage sludge would be more desirable for agricultural use, but the drying process is an extra expense which treatment plants hope to avoid.

Microbial activity can be used as a gauge of the physical and chemical quality of soils. Aerobic microorganisms are sensitive to adverse soil conditions and respond to optimal soil aeration and nutrient availabilty at levels which would also affect plant growth. The majority of microorganisms in a well drained soil are aerobic heterotrophs which generate energy through the process of respiration. In this process organic compounds are oxidized, resulting in the release of CO_2 and the utilization of O_2 as a terminal electron acceptor. (Atlas and Bartha, 1981) The goal of this study was to utilize the microbial respiration rate of aerobic heterotrophs as an index of the degree of aeration of compacted soils and soils amended with liquid sewage sludge. Aerobic microbial metabolism is restricted by limited aeration and the metabolic rate can be monitored by measuring the CO_2 evolution rate from the soil. In this research, aeration will be used as the indicator of the soil physical condition. The analyses will involve the following subobjectives:

1) To assess the existence of soil compaction when sewage sludge is applied at high rates under field conditions using conventional tillage.

2) To define a method of using microbial respiration as an index of soil aeration.

3) To determine the levels of soil bulk density and moisture content at which aeration is limiting to aerobic microbial activity.

4) To determine the moisture content at which aeration is limiting to microbial respiration in a sludge amended soil compacted to 1.4 Mg m^{-3}.

5) To assess the relative effects of various soil amendments, including two application rates of sewage sludge, on the level of aeration in a compacted soil.

LITERATURE REVIEW

Soil organic matter, in production agriculture in the US, has been steadily depleted over the past few decades by continuous cultivation and the use of inorganic chemical fertilizers. Fertilizers supply the essential plant nutrients, but not the carbon source needed to maintain the organic matter content of the soils. Organic matter contributes to the chemical, biological and physical properties of a fertile agricultural soil, and substantial increases in crop yields have been recorded when organic matter is added in addition to inorganic fertilizer (Stroo and Jenks, 1985; Somani and Saxena, 1975; Mays et al., 1973). Current agricultural practices are estimated to deplete 20% of the soil organic matter initially present in virgin soil after the first 20 years of cultivation, an additional 10% in the next 20 years, and 7% in the subsequent 20 years (Stevenson, 1982). Declines in soil productivity since the beginning of the "green revolution" have been attributed to this decrease in soil organic matter.

The use of organic residues as fertilizer has been discouraged by the low nutrient content, and the cost of hauling and spreading the quantitiy of manure or compost needed to supply the nutrients required by a given crop. But this criticism is based on the assumption that organic residues and chemical fertilizers are equivalent soil amendments. Current research has demonstrated that there are major differences in the benefits derived from inorganic and organic nutrient sources (Mays et al., 1973; Somani and Saxena, 1975).

Chemical Nature of Soil Organic Matter

The decomposition of plant and animal residues is a basic biological process continuously occurring in the soil. Carbon and nitrogen are cycled between the atmosphere and the organic compounds of plants and animals. Soil organic matter is composed of the residues from plant and animal organic compounds, which consist primarily of sugars, hemicellulose, cellulose, lignin, chitin, protein, fats and waxes. These components are either converted to simple inorganic compounds or to soil humus.

The chemical properties of soil humus, the only stable component of soil organic matter, are characterized by Stevenson (1982). Carbon compounds incorporated into humic material represent a resistant fraction with an average residence time of 250 to 2500 years. The exact chemical structure of humic material is unknown yet several theories explain the origin and general chemical properties of this resistant organic compound. The aromatic structure of humic materials has been found to have chemical properties characteristic of lignins. The polyphenol theory explains that lignins are modified by microorganisms to phenolic aldehydes and acids. These molecules are utilized by microorganisms in combination with celluloses and other non-lignin degradation products to form polyphenols. The polyphenols are converted to quinones which combine with amino compounds to form humic and fulvic acids. In general, the humic materials are characterized as molecules with a 100:10:1:1 ratio of C:N:P:S; a high molecular weight (1000-300,000g); aromatic di and trihydroxyl phenols linked by oxygen, nitrogen, and sulfur bonds; a high density of reactive functional hydroxyl and carboxyl groups; and numerous sites for sugar and amino acid side chains which can be added or mineralized over time. The humic materials have been divided into fulvic acids, humic acids and humin according to their solubility in acid or base. The resistance to degradation of these humic substances is attributed to the aromatic structure and the bonding of the organic acids to clay particles leading to incorporation into soil aggregates.

The rate at which the inorganic components of organic matter become available to plants is dependent upon the chemical composition of the specific compounds. Sugars, cellulose, hemicellulose and proteins are readily decomposed, while the more resistant compounds such as chitin, fats, and waxes are more slowly decomposed (Miller, 1973). Nitrogen from compounds with a C:N ratio less than 25:1 is mineralized and readily available to plants, while the nitrogen in compounds with a higher C:N ratio is immobilized as microbial biomass. Nutrients incorporated into microbial tissue are released gradually upon the death and decomposition of the cells. Components incorporated into the soil humus have the longest residence time, with the exception of the sugar and amino acid side chains which are continuously added and mineralized. In addition, small amounts of nutrients from the stable backbone of the humic material are released each year (Stevenson, 1982).

Sewage sludge contains many of the organic materials found in plant and animal residues. Organic matter constitutes 50% of the solid fraction of the sludge while the remaining solid portion consists of inorganic components (Guidi, 1981). The average organic carbon content is 25% on a dry weight basis (Miller, 1973). Most of the soluble organic matter is rapidly converted to CO_2, H_2O, and inorganic compounds during the aerobic treatment process. The solid organic portion of the sludge contains cellulosic products, microbial cells, and the microbial by-products synthesized during the treatment process. The relative ease of decomposition of the major part of the sludge is indicated by the frequently used term "volatile solids." Yet part of the cellulosic portion of the sludge is modified and incorporated into the soil humus. Sewage sludge originating from domestic wastes and wastes from food processing plants contains solid material predominantly cellulosic in nature. The hydrolysis of the cellulose chain is a rate limiting step in the degradation of cellulose and thus much of the cellulosic material remains in the sludge. Most of the organic nitrogen in the sludge is tied up in the microbial cells. Sludge typically has a C:N ratio less than 10. The bacterial slime produced during the treatment process is primarily composed of polysaccharides and is rapidly decomposed when incorporated into the soil (Broadbent, 1973).

Contribution of Organic Matter to Soil Chemical Properties

Organic matter is a source of most of the elements essential for plant growth. Chemical fertilizers typically provide these nutrients in soluble forms which can be volatilized, leached or precipitated in insoluble complexes, if not absorbed immediately by the plant. Significant percentages of inorganic nitrogen amendments are often lost due to the volatilization of ammonia, the leaching of nitrates, or the denitrification of nitrates in anaerobic microsites. Organic residues provide a slow release of nitrogen throughout the growing season as organic matter is mineralized by micoorganisms (Donahue, Miller, Schickluna, 1983). Research has shown that soil C:N ratios decrease with the high application rates of dry sludge compost or anaerobically digested liquid sludge indicating an increased rate of available nitrogen. Previous work has demonstrated that inorganic nitrogen was still being released 2 years after sludge was applied, although the majority of nitrogen is mineralized during the first year (Epstein et al., 1976; Lindeman, 1988). A large portion of the phosphate applied as superphosphate also becomes unavailable to plants due to fixation by the polyvalent cations calcium, iron and aluminum. The slow release of phosphate by mineralization of organic matter allows plants to absorb the phosphate before fixation occurs (Epstein et al., 1976).

Soil humus has additional influences on soil chemical properties. Humus is a chelating agent and forms stable complexes with polyvalent cations. The chelation of Fe and Al enhances the availability of phosphorous by limiting fixation (Stevenson, 1982). Humic material also chelates micronutrients, keeping them soluble and available for absorption by plants (Stevenson, 1982). The hydroxyl and carboxyl groups of humic and fulvic acid molecules ionize at slightly acid to basic pH levels, thus increasing the soil cation exchange capacity and the availability of inorganic cations (Allison, 1973). Various studies have demonstrated the increase in soil humus content resulting from applications of sewage sludge, manures and composts (Somani and Saxena, 1975; Epstein et al., 1976; Koskella, 1981).

Contribution of Organic Matter to Soil Biological Properties

Biological properties of the soil are significantly stimulated by the addition of organic residues. The soil is a living system and microbial activity is an essential component of a productive agricultural soil. Microorganisms require the same essential nutrients as plants and thus respond to the increased carbon supply and nutrient availability provided by organic residues (Pera et al., 1983; Stroo and Jenks, 1985). Microorganisms help to generate soil humus through decomposition and resynthesis of added organic matter and are responsible for the slow release of nutrients by the mineralization of organic residues and humus. Specific microorganisms also add to the nutrient source of plants. Organic matter provides an energy source for the freeliving heterotrophic N-fixing bacteria and actinomycetes. Other heterotrophs rely on organic matter as an energy source for the oxidation of elemental sulfur converting it to a form available to plants (Alexander, 1977). In addition, carbonic acid generated from CO_2 released during respiration, and organic acids secreted by micoorganisms solubilize small amounts of fixed phophates (Allison, 1973). Plant growth factors and toxins are products of microbial metabolism and microbial decomposition of organic residues. These compounds can either stimulate or inhibit plant growth depending on their structure and relative concentrations. Plant pathogenic populations are also reduced by the increased competition from heterotrophs stimulated by soil organic matter additions (Stevenson, 1982; Curl and Truelove, 1986).

A final important contribution by micoorganisms is the improvement of soil structure. Bacteria produce polysaccharides which cement soil particles to form stable aggregates, which improve the granular structure of the soil and are less susceptible to compaction. Polysaccharides are large, linear, flexible carbohydrate molecules capable of attatching to clay particles at multiple sites by cation bridges, hydrogen bonding, van der Waals forces and anion absorption mechanisms. Some organic products are hydrophobic, thus reducing the wettability and swelling of the organo-clay complex and increasing the aggregate stability (Hillel, 1982). It has been found that the biomass of bacterial cells added to a soil is proportional to the increase in aggregate stability. When the polysaccharide gum is removed from bacterial cells, the effect of bacteria on soil structure is reduced. Conversely, when polysaccarides alone are added to the soil the effect is similar to that of the intact bacterial cells. Thus polysaccaride gums have been isolated as the principal cementing agents responsible for improving aggregate stability (Lynch, 1987). Polysaccharides are readily degraded by microorganisms, thus the aggregating effect decreases over time. In spite of this degradation, increased aggregation has been observed in soils 6 to 12 months after amendment with sewage sludge (Guidi, 1981). Metzger et al. (1987) defined the dynamics of aggregation as a two phase system. An initial "aggregative" phase following a high level of microbial activity, resulting in the formation of water stable aggregates, followed by a "stabilization" phase. In the stabilization phase part of the organic cementing agents decompose, but the remaining aggregates are stabilized due to such processes as the binding of organic molecules to clay surfaces. In general, residues must be added to the soil annually to maintain the increased microbial production of polysaccharides. Likewise, fungi form soil aggregates through the secretion of polysaccharides and the growth of fungal hyphae around soil particles. Fungal hyphae become entangled around soil particles, maintaining these particles in aggregate form. Some research suggests that the formation of water stable aggregates is best correlated with fungal activity (Metzger et al., 1987).

Contribution of Organic Matter to Soil Physical Properties

Considerable research has been done on the effects of manure, compost and other organic residues on soil structure, but the work on the effects of sewage sludge amendments is more limited. Soil structure refers to the arrangement and organization of the primary soil particles (sand, silt, and clay) into secondary aggregates. Soil structure affects the porosity and the shape and distribution of the pores, thus affecting the transmission of air and water in the soil. Parameters affected by soil structure include infiltration rate, hydraulic conductivity, water retention and aeration. These parameters strongly influence root growth and respiration, microbial activity, and wind and water erosion (Hillel, 1982).

Organic constituents are thought to influence the aggregation of soil particles in three ways. First, organic substances have been found to bind clay particles together. Both clay particles and dissociated organic acids are anions, but the binding of these anions is possible with divalent and trivalent cations (Ca^{2+}, Fe^{3+}, and Al^{3+}) serving as salt bridges between the clay and the acid (clay - M - OOCR). Hydration water of the exchange cation can also form a hydrogen bond with the organic anion. Hydrogen bonding results when a hydrogen atom serves as a bridge between two electronegative atoms, holding one by a covalent bond and the other by purely electrostatic forces (Morrison and Boyd, 1978). Thus hydrogen atoms of water molecules bind covalently to oxygen atoms and have an electronegative attraction for clay particles and organic acids. Other H-bonds also form between polar portions of the organic acid and absorbed water molecules or oxygens on the clay surface. These H-bonds may be weak, but they are additive due to the large size of the humic or fulvic acid molecules. Large organic acid molecules bind to several clay particles and hence function as cementing agents to form high stability aggregates. The second and third methods in which organic constituents influence soil aggregation are the production of bacterial and fungal polysaccharides and the physical entanglement of fungal hyphae as mentioned above (Stevenson, 1982).

Research has demonstrated that the organic matter content of soils has a significant effect on the soil structure. Khaleel et al. (1981) reviewed field experiments from 12 sources with 21 soil types, 7 waste types and 8 crop types and found a linear correlation between the percent increase in soil organic carbon and a percent decrease in soil bulk density. He attributes the decrease in bulk density to a dilution effect of mixing organic matter with the mineral components of the soil. Decreased bulk density implies an increase in porosity which leads to improved soil aeration, water retention at low water potentials, permeability and infiltration. Mays et al. (1973) found decreases in both bulk density and compression strength of the soil after incorporation of compost over a two year period. Liquid wastes were found to contribute less to the improvement of soil physical properties because of a lower percent organic carbon content. Somani and Saxena (1975) found that organic residues with high C:N ratios such as wheat straw and rice hulls decompose more slowly, thus decreasing bulk density and increasing the soil structural index more than manures with narrower C:N ratios. Yet organic matter with narrow C:N, C:P, and C:S ratios causes a significant increase in soil N, P, S, and humus levels while wheat straw and rice husks with high C:N, C:P, and C:S ratios have little influence on humus levels and immobilize N, P, and S.

Increases in the soil water holding capacity are also attributed to increased soil organic matter content. Water holding capacity is controlled by the number and size distribution of pores and the specific surface area of the soil, both of which are increased with organic matter additions (Khaleel et al., 1981). Epstein (1975) reported that soil treated with digested sludge on a 5% dry weight basis retained 10 times more water than the control soil. In soils treated with 240 metric tons ha^{-1} of anaerobically digested sludge, 20% increases in moisture content and 6% increases in plant available water were reported. Epstein concluded that the increases in water content and water retention could significantly reduce water stress to plants during the growing season.

Other physical properties such as infiltration rate and hydraulic conductivity would presumably be increased as well due to decreases in bulk density, but little work as been done in this area. Increased infiltration caused by the increased number of large pores from improved aggregation, also helps a soil to resist erosion. Water more readily percolates down through the soil instead of running off the surface (Stevenson, 1982). Wei et al. (1985) found increased infiltration rates, moisture contents and aggregate stability in soils treated with high rates of dewatered sludge. Epstein (1975) found increases in hydraulic conductivity after the addition of sewage sludge with 5% solids, but the effect decreased over time as the organic matter was mineralized.

The Use of Sewage Sludge as a Soil Amendment

In addition to the potential positive aspects, various toxic elements are also associated with the use of sewage sludge as a soil amendment. The toxic elements fall into the three categories of heavy metals, organic compounds, and pathogenic microorganisms. Heavy metals presenting potential hazards include boron, cadmium, chromium, cobalt, copper, mercury, nickel, lead, and zinc (Chaney, 1973), although those receiving the most attention are Cd, Cr, Cu, Ni, Pb, and Zn. The concentration of the heavy metals in sewage sludge is dependent on the industrial sources of the waste material. Numerous studies have investigated the fate of these elements in the soil, the degree of phytotoxicity, and the possible toxicity to animals feeding on plants grown on sludge amended soils (Chang et al., 1984; Rappaport et al., 1987; and Dressler et al., 1986). Their research has shown that 90% of the deposited metals are retained in the top 0 - 15 cm of soil. Although plant absorption of heavy metals was found to increase with increasing sludge applications, phytotoxicity was not observed, and the plant metal concentrations remained within the normal range for the respective plants. Accumulations of Cd and Zn were also found in the tissue of swine, cottontail rabbit, ring-necked pheasant and meadow vole feeding on vegetation grown on sludge amended soil, but the accumulations never attained hazardous levels. Further research is needed to evaluate the long term effects of heavy metals on consumers feeding on crops grown on sludge amended soils.

The concentration of organic toxins reaching the soils is usually low and the majority of these toxins are absorbed to soil particles and can be metabolized or detoxified by microorganisms. Potential organic toxins include phenolic compounds, chlorinated hydrocarbon pesticides, chlorinated biphenyls, detergent residues and petroleum products. It has been concluded that, except where sludge is consumed directly and in large amounts, the consumption of contaminated soils or crops is unlikely to lead to ingestion of toxic organic compounds at levels in excess of the acceptable daily dose (Naylor and Loehr, 1982; Conner, 1984).

The pathogenic microorganisms include the bacteria Salmonella, Shizella, Mycobacterium, and Vibrocomma; the hepatitus virus, enteroviruses, and adeno viruses; and the protozoan Endomoeba histolytica.

The anaerobic digestion process eliminates a significant number of the pathogenic microorganisms, but not all. Research has shown that pathogens are largely adsorbed near the surface, and are eliminated from the soil rather rapidly through interaction with soil microorganisms. However, further research is needed concerning the movement and survival of viruses in soils (Miller, 1973).

Current research has found only low levels of pollutants in the anaerobically digested sewage sludge from the Ina Road Wastewater Treatment plant in Tucson, AZ. Of primary concern is the percolation of macronutrients to the groundwater (specifically nitrates). Nitrates are found at higher levels in sludge amended soils than soils fertilized with chemical fertilizer. Among the heavy metals, only low levels of copper were detected and organic pollutants were present at low levels if at all (M.M. Minnich, personal communication).

The use of sewage sludge as a soil amendment provides a partial solution to the problem of waste disposal. Sludge removed from waste water treatment plants is a liquid waste rather than a solid waste disposal problem. Dewatered sludge has a higher percent solids and thus can be applied at higher rates, but dewatering or drying of sludge is expensive, thus constituting a less economical method of disposal than the direct use of liquid sludge (Dean and Smith, 1973). Anaerobically digested liquid sludge typically contains less than 5% solids (Sommers, 1977).

Higher sludge application rates provide more significant improvement of soil chemical and physical properties and a more economical method of waste disposal. Yet application of high rates of liquid sludge is difficult because more passes over the field are required. The soil is well saturated after one sludge application and fine-textured soils may not dry completely before the second and third applications, due to the high level of water retention. Fine-textured soils have a higher percentage of micropores than coarse-textured soils and more water is retained in the smaller pores due to capillary forces, which are inversely proportional to pore diameter. In addition, there is a higher retention of water molecules in clay soils due to their electronegative attraction to the negatively charged clay particles (Hillel, 1982). Heavy machinery is utilized for the application of sludge and moist soils are more readily compacted than drier soils. The resulting compaction increases soil bulk density, thus decreasing soil porosity. Thus the potential for improved soil structure resulting from high sludge application rates may be negated by increased soil compaction caused by sludge application methods.

The Effects of Compaction on the Soil Physical Condition

Compression of the soil refers to a process where the soil volume is decreased under an externally applied load. The soil volume consists of the mineral and organic soil solids and the air or water which fills the pore spaces. The density of the soil solid components is referred to as the particle density which averages 2.65 Mg m^{-3}. In contrast, the density of the soil volume is referred to as the bulk density and can vary from less than 1.0 to 1.8 Mg m^{-3}. The variation between the particle density and the soil bulk density is a function of the soil porosity. The soil porosity represents the total volume of soil pores or voids which vary in size and shape according to the texture and structural development of the soil. The compression of unsaturated soil is called compaction, where soil air is excluded from the voids of the soil matrix (Gupta and Allmaras, 1987). The proportion of soil macropores is reduced in a compacted soil thus decreasing soil aeration at water tensions close to field capacity and impeding drainage (Hillel, 1982).

Three factors define the effects of compaction on soil structure. These factors include the limitation of porosity critical for both gaseous diffusion and drainage, the increased shearing of aggregates resulting from the applied load stress, and the increase in soil resistance critical for root growth (Gupta and Larson, 1982). Aeration is not only limited by a reduction in the number of soil macropores, but also by the level of microbial and root respiration in the soil. Under conditions of limited gaseous diffusion, O_2 can become depleted and CO_2 can accumulate if respiration levels are significant. The increased shearing of soil aggregates destroys the structure of the soil, thus further reducing the proportion of soil macropores. Finally, numerous studies have demonstrated the restriction to root growth caused by increased soil strength. Externally imposed pressures of just 0.02 MPa have been shown to reduce the rate of elongation of barley roots by 50%, and pressures of 0.05 MPa cause a 80% reduction in root extension (Hillel, 1982).

Aeration was identified as a significant index of the level of soil compaction or the condition of soil structure. Not only is soil aeration directly affected by mechanical compaction of the soil, but the degree of soil aeration is one of the most important determinations of soil productivity. Poor aeration not only restricts root and microbial respiration, but can decrease the permeability of roots to water (Hillel, 1982).

Microbial Respiration as an Index of Soil Aeration

The effect of compaction on soil aeration is a parameter which is difficult to evaluate. The group of processes referred to by the term soil aeration are incompletely understood, and difficult to measure. Thus soil aeration is often measured by indirect determinations of air-filled porosity which are thought to be indicative of soil aeration as a whole. The air-filled porosity is calculated from measurements of soil bulk density at a specific moisture content. But the available air may not be uniformly distributed and equally available to microorganisms and plant roots throughout the soil. In addition, air-filled porosity may not be an accurate indicator of gaseous diffusion in the soil because a portion of the air might be trapped in pockets in a wet soil and not actively exchanged with the atmosphere. Another traditional approach is the measurement of CO_2 and O_2 concentrations in the soil air, using gas chromatographic techniques or electrodes. These methods tend to be more representative of the dynamic exchange of air in the soil than the measurement of air volume alone, but the sampling procedures for both methods present numerous problems. A different approach is the determination of air permeabiltiy by measuring the transmission of air through the soil in response to a pressure gradient. This method provides information concerning the relative continuity and volume of pores, but fails to indicate the existence of isolated air pockets or liquid envelopes surrounding roots (Hillel,1982). Plant growth is another common indicator of the effects of compaction, but root elongation is not only affected by limited aeration, but by increased soil resistance as well and thus cannot be used as an index of soil aeration.

It has been shown that aerobic microbial respiration is also restricted by limited aeration (Miller and Johnson, 1964; Linn and Doran, 1984a). Aerobic microorganisms include photoautotrophs, chemoautotrophs and heterotrophs, with heterotrophs predominating among the soil bacteria. Heterotrophs generate energy through the oxidation of organic compounds in the respiration process. In this process, O_2 functions as the terminal electron acceptor. Thus limited soil aeration would cause a decrease in the aerobic microbial metabolic rate due to a lack of O_2. Carbon dioxide is released from the oxidation of organic materials, thus the CO_2 evolution rate can be utilized as a measure of the microbial metabolic rate (Atlas and Bartha, 1981) and an index of soil aeration.

Experimental evidence has demonstrated the effect of compaction on microbial activity. The nodulation of soybean plants is reported to be reduced by 30-40% on plants grown in soil compacted by wheel traffic (Voorhees et al., 1976; Soane et al., 1982). Anaerobic microbial activity such as denitrification is increased in nontilled soils which are typically wetter and more compact than those under conventional tillage, and thus become saturated and anaerobic more frequently (Rice and Smith, 1982; Linn and Doran, 1984a). Aerobic microorganisms exist in soil pores of all sizes, thus a measurement of their combined respiration provides a useful index of the overall level of soil aeration.

Microbial activity is both a useful index of soil chemical and physical properties and a vital component of a productive agricultural soil. Alexander (1977) upholds that the soil respiration rate is the best measure of microbial activity in the soil. Critical values of air-filled pore space for microbial respiration agree with minimum values required for plant growth (Bridge and Rixon, 1976). Linn and Doran (1984b) demonstrated that aerobic and anaerobic microbial activity are a function of both the porosity and the soil moisture content. Thus the effects of soil compaction must be evaluated as a function of soil moisture content. Linn and Doran further reported that the percent of pore space filled with water was highly correlated with CO_2 production ($r=0.892$, $p<0.001$). Thus microbial activity can be utilized as an aeration index evaluating the effects of compaction and sludge amendments on the physical strucure of the soil.

MATERIALS AND METHODS

Field and laboratory studies were conducted in order to investigate the effects of compaction and sewage sludge amendments on the physical structure of the soil. The field study was designed to assess the impact of various application levels of anaerobically digested sewage sludge on the level of soil compaction. The laboratory study was conducted to evaluate the relative effects of compaction, moisture content and soil amendments on soil structure as measured by the level of aeration in the soil. Microbial respiration was utilized as an index of soil aeration. The anaerobically digested liquid sewage sludge for both studies was obtained from the Ina Road Wastewater Treatment Plant in Tucson, Arizona.

Field Study

Measurement of compaction in the soil is difficult due to the spatial variability of field soil. The limited soil volume evaluated by penetrometer readings and bulk density measurements is rarely representative of a large area of field soil. Although there is limited data on the changes in hydraulic properties of soils resulting from applied loads, studies have demonstrated that compacting loads of 0.346 MPa at field capacity on sandy loams and finer textured soils reduced the infiltration rates to less than 0.1% of values obtained when air-dry soils were compacted. In general, excessive compaction impedes the flow of water in the soil (Gupta and Allmaras, 1987). Thus the relative movement of a wetting front through the soil profile was used as an indicator of the level of compaction of different treatments in the field, with a restriction in water movement indicating increased compaction. It was proposed that the measurement of water flow through the soil is a more representative indicator of the level of compaction in the soil profile than other more traditional methods.

The experiments were conducted on field #C-4 at the University of Arizona's Marana Agricultural Center. A 4.25 ha field was planted with wheat using the following field operations. Prior to application of the liquid sewage sludge, the field was ripped with a blade which penetrated a maximum of 50 cm, disked, and the positions of the beds were marked by shallow listing. The sewage sludge was then injected 15 to 30 cm below the soil surface and inorganic fertilizers were surface applied, and incorporated into the soil by disking. The field was then disked, listed to make planting beds, preirrigated, and harrowed with a rotary harrow to break up the clods. Wheat was planted with a grain drill and the field was irrigated as needed throughout the growing season.

The field used was divided into 8 replicate blocks of 4 treatments. Each block was 6 rows wide having dimensions of 6.10 m by 175.26 m or 0.1068 ha. The treatments were as follows:

1) Recommended levels of nitrogen, phosphorous, and potassium for wheat from inorganic fertilizers (168, 56, and 0 kg ha^{-1} N, P, and K, respectively).
2) Anaerobically digested liquid sewage sludge applied at a rate to supply the recommended amount of nitrogen for wheat (2.4 Mg sludge ha^{-1} on a dry solids basis).

3) Inorganic fertilizer supplying N, P, and K at the same levels as in the sewage sludge used in treatment 2 (168, 57, and 6.7 kg ha^{-1} N, P, and K, respectively).

4) Sewage sludge at three times the rate used in treatment 2 (7.2 Mg sludge ha^{-1} on a dry solids basis).

The sludge application rate was calculated using N-mineralization constants in order to determine the plant-available N. (See Appendix 1)

Sewage sludge was applied at the low rate by one pass of the injector. Three passes of the injector were required in order to apply the high rate. Due to the liquid nature of the sludge, a drying period of several days to a week was required between each of the applications for the high sludge rate to reduce compaction.

The relative compaction of each treatment was determined by monitoring the movement of water through the soil profile. At each field experiment site a 2.13 m by 2.13 m area was bermed and three neutron access tubes were placed in the furrows within each bermed area. While installing the access tubes, the neutron probe was calibrated by simultaneously taking soil samples with a soil probe and measuring the moisture content with the neutron probe at 40, 60, 90, and 105 cm. The probe was designed to sample a fixed volume of soil with minimal disturbance so that the bulk density and the moisture content of the soil at each depth could be determined from the respective samples. The bulk density and gravimetric moisture content of each sample were determined in order to establish a linear correlation between the neutron probe count ratio and the soil volumetric moisture content. Each bermed area was then filled with a specific quantity of water and the moisture content monitored at 30, 40, 50, 60, 70, 80, 90, and 105 cm using the neutron probe. Five hundred and ten liters of water were added per bermed area the first time the experiment was conducted and 567 liters the second time. More water was used the second time due to the drier soil conditions which allowed for a faster intake rate. The moisture content was measured at depth intervals immediately before water application and at 24 and 48 hours following the water application. The moisture levels at 48 hours were found to be consistently equal to or less than those taken at 24 hours, indicating that the water content had equilibrated within the soil profile and no additional measurements were required.

The experiment was conducted twice; once on March 16, 1987, 2 months following planting, and a second time on June 25, 1987, immediately prior to harvest. Two sites were utilized, one on each side of the field in order to represent variations in soil characteristics found within the field. At each site, a bermed area was located on the two sludge treatments and the inorganic control. Each berm was placed approximately 23 meters from the end of the field to avoid border effects. The same procedure was followed each time the experiment was conducted with the exception of the variation in the quantity of water added to the bermed areas.

Laboratory Study

The impact of compaction and organic amendments on the physical structure of the soil was evaluated by measuring microbial respiration as an index of the level of aeration in soil samples. Microbial respiration rates were monitored following a modification of the procedure of Linn and Doran (1984). The soil used was a Pima clay loam soil (fine-silty, mixed, thermic Typic Torrifluvents) collected from the surface horizon of the field study site, air-dried, ground and sieved (2 mm), and stored at room temperature.

Chemical and Physical Analysis of Soil and Anaerobically Digested Sewage Sludge

Total organic carbon was determined for both soil and the sewage sludge using the wet combustion method apparatus described by Allison (1960). Samples were pretreated with 5% $FeSO_4$ and brought to a boil to eliminate inorganic carbon. The wet combustion involved a digestion with potassium dichromate and a mixture of concentrated sulfuric and phosphoric acids. The CO_2 evolved was passed through a purifying train and was collected in a Nesbitt bulb filled with Ascarite. The purifying train consisted of KI and $AgSO_4$ traps for removing Cl_2 and a H_2SO_4 trap for H_2O and N_2 absorption. The quantity of organic carbon was determined from the amount of CO_2 evolved.

The nitrogen content of the Pima clay loam and sewage sludge was analyzed by the Kjeldahl technique as outlined by Bremner and Mulvaney (1982). Total soil nitrogen was determined using the Olsen modification which included a pretreatment with $KMnO_4$ and H_2SO_4 followed by reduced Fe in order to reduce the oxidized forms of inorganic N (NO_3^- and NO_2^-). The soil was then digested with H_2SO_4 and a catalyst mixture containing K_2SO_4, $CuSO_4$ and Se. After digestion, NaOH was added to the sample which was then steam distilled and the NH_3 gas collected in a boric acid indicator solution. The boric acid solution was titrated with 0.01 M $KH(IO_3)_2$ and the nitrogen concentration calculated from the amount of titrant utilized. Organic and inorganic N were determined separately for the sludge samples. Combined organic and NH_4^+-N were determined according to the above procedure without the Olsen pretreatment. The NH_4^+-N was then determined separately by the distillation and titration of an undigested sample. The organic N was calculated by substracting the quantity of NH_4^+-N from the total N. Nitrates were determined by the analysis of filtered sewage sludge using ion exchange chromatography.

The soil pH of the Pima clay loam soil was determined by the analysis of a soil saturated paste extract. The soil and sludge moisture contents were determined gravimetrically by drying representative samples overnight in 105°C and 60°C ovens, respectively.

General Procedure for Individual Studies

Four studies were conducted using the following methods. Air dry Pima clay loam soil (0.4 g g^{-1} moisture) was placed in 80.5 cm^3 soil moisture cans. Each can was filled to capacity and contained an average of 90 g of soil. The moisture content was adjusted to the desired level and the samples compacted to the specific bulk density required. Inorganic fertilizer, sludge, or alfalfa soil amendments were added to each sample prior to ajusting the moisture content and compacting the soil (amendments varied with the experiments).

The soil moisture content was adjusted gravimetrically by adding water to the surface of the soil in three separate aliquots in order to equally distribute the water throughout the samples. A third of the water was added to a third of the soil followed by another third of soil and water until the desired amount of water had been added to the full soil sample. All moisture values were expressed on a mass basis. Moisture contents were monitored and adjusted periodically throughout the incubation period and determined gravimetrically at the conclusion of each study.

The soil samples were then artificially compacted following a modification of the procedure of Gupta and Allmaras (1987). Experimental setups use either triaxial or uniaxial compression to artificially compact soil samples. In the triaxial setup, the soil sample is placed in a rubber membrane and subjected to applied stresses in the vertical and horizontal directions. In the uniaxial setup the sample is placed in a metal mold and subjected to applied stress in the vertical direction only. Koolen and Kuipers (1983) found that bulk density varied primarily with the vertical load and only slightly with horizontal applied pressure. Thus it was determined that compaction of loose soil in a rigid metal cylinder by a piston was a sufficient means of simulating field compression. For the present studies a metal piston was designed with the specific dimensions of the soil moisture cans (Figure 1). The moisture cans were filled with a specific mass of soil which was then compacted to varying volumes depending on the bulk density desired. The compaction was accomplished by inserting the piston into a moisture can filled with soil,

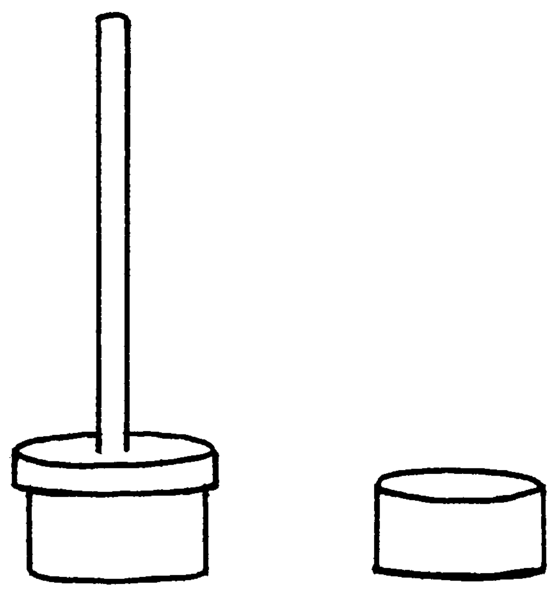


Fig. 1. The piston used to compress soil samples in the accompanying soil moisture can.

to which water and amendments had previously been added, and manually applying pressure until the soil was compacted to the predetermined volume require to achieve the desired bulk density.

Prepared samples were placed in 946 ml mason jars and sealed with air tight lids. Each lid was fitted with a rubber serum stopper for gas sampling. The jars were incubated at 27°C. Samples were taken by simultaneously placing one end of a double ended needle in the serum stopper and the other end in a 10 ml vacutainer. Gas samples were stored in the vacutainers at room temperature until analyzed. After each sampling period, jars were opened to allow for equilibration of the headspace atmosphere with atmospheric CO_2 and O_2 levels to prevent the depletion of O_2 or the accumulation of toxic levels of CO_2.

Gas samples were analyzed for CO_2 concentration using gas chromatographic techniques. One cm^3 samples were drawn from the vacutainers with a gas syringe to be used for analysis. Carbon dioxide concentrations were analyzed using a Hewlett Packard thermal conductivity detector at a temperature of 150°C, a column oven temperature of 60°C, an injection port temperature of 250°C, and helium as the carrier gas. The carrier gas flow rate was 65 ml min^{-1}. The column used was a concentric column containing a 3.175 mm inner column packed with Porapak for CO_2 detection surrounded by a 6.35 mm outer column packed with Activated Molecular Sieve for O_2 detection. The column was calibrated to measure percent CO_2 and percent O_2 in a gas sample of a specific volume.

Study 1

The objective of this experiment was to identify the general physical conditions under which aeration became limiting to microbial respiration in a clay loam soil. The soil samples were amended with urea and treble superphosphate at rates of 75.4 mg kg^{-1} N and 11.4 mg kg^{-1} P, respectively, levels comparable to the chemical fertilizer rates used in the field study. Bulk densities and moisture contents were adjusted to provide samples with a range of water filled pore space (WFP) values, in order to determine the point at which soil aeration became limiting to microbial activity. Linn and Doran (1984) identified the optimal WFP value for microbial respiration as 60% thus the treatments were designed to provide a range of values about this optimum. The percent WFP was calculated using the gravimetric moisture content and the bulk density (see Appendix 2). The percent WFP is synonymous with the degree of soil saturation (percent saturation). Triplicate samples of nine treatments were established in a two factorial design, the first factor being bulk density and the second being moisture content. Soils were compacted to bulk densities of 1.1, 1.4, and 1.6 Mg m^{-3} to simulate the range of possible field conditions. At each bulk density samples were maintained at 0.10, 0.20, and 0.24 g g^{-1} moisture. The samples were placed in the mason jars and gas samples were taken from the headspace atmosphere of each jar every 24 hours for the first four days and approximately every 2 days for the remainder of the 18 day incubation period.

Study 2

Based on the results observed in the first experiment, this experiment more specifically identified the moisture content at which aeration became limiting to microbial respiration in a sludge amended soil compacted to a bulk density representative of field conditions. Soil samples were amended with sewage sludge at the rate of 1.38 mg sludge g^{-1} soil (dry solids basis), a rate supplying nitrogen at a level equal to the low sludge rate used in the field study. The moisture contents of triplicate samples were adjusted to 0.9, 0.20, 0.22, 0.24, 0.26, 0.28, and 0.30 g g^{-1}. All samples were then compacted to 1.4 Mg m^{-3}, a bulk density typical of field conditions as indicated by Post et al. (1978). The moisture contents represent a range from permanent wilting point to saturation for the bulk density utilized. Samples were placed in mason jars and gas from the headspace of the jar was sampled every 24 hours for the first 4 days and approximately every other day for the remainder of the 20 day incubation period, as in the first study.

Study 3

The third experiment had two objectives. The first objective was to evaluate the effect of the sludge amendment on the microbial respiration rate. Thus triplicate samples of sludge amended and unamended soil were adjusted to a moisture content of 0.24 g g^{-1} and compacted to a bulk density of 1.4 Mg m^{-3}. The CO_2 evolution rate of the unamended samples was then compared to that of the amended samples throughout the incubation period.

The second objective was to replicate the second experiment in order to confirm the results obtained. Thus triplicate samples of sludge amended soil were adjusted to moisture contents of 0.24, 0.26, 0.28, and 0.30 g g^{-1} and compacted to a bulk density of 1.4 Mg m^{-3}. This range of moisture contents represented the critical range in which aeration became limiting to microbial respiration in the second study.

All samples for this study were placed in mason jars and sampled in the same manner as in the first two studies over a 26 day incubation period. The incubation period was extended to further confirm the results observed in the second experiment.

Study 4

The objective of the fourth experiment was to evaluate the effects of various soil amendments on soil aeration. Organic amendments have been shown to stimulate microbial production of polysaccharides which enhance the aggregation of soil particles, thus improving the structural stability of the soil (Guidi, 1981; Lynch,1987; Metzger et al., 1987). The soil samples were adjusted to a specific moisture content and bulk density previously identified as limiting to soil aeration. It was proposed that an improved soil structure would lead to better soil aeration and a significant increase in CO_2 evolution.

Four replicates of five treatments containing the following amendments were utilized: a control with no amendment; sewage sludge at the low rate of 1 mg sludge g^{-1} soil (dry solids basis); sewage sludge at a high rate of 3 mg sludge g^{-1} soil (dry solids basis); inorganic fertilizer amendment supplying 95.2 mg g^{-1} N and 14.7 mg g^{-1} P as urea and treble superphosphate, respectively; and 0.5% dried alfalfa. The sludge rates were determined to supply nitrogen at rates equal to those of treatments 2 and 4 in the field study. Amendments were added to the samples, the moisture content was adjusted to 0.26 g g^{-1} and the soil compacted to a bulk density of 1.4 Mg m^{-3}. The samples were left for a 90 day incubation period to allow for decomposition of soil amendments and synthesis of microbial byproducts which might enhance structural stability. The moisture content was adjusted gravimetrically as needed. During the last 7 days of the incubation period the samples were left to dry to 0.8 g g^{-1} moisture after which microbial activity was stimulated by amendment with a 2% glucose solution with NH_4Cl supplying nitrogen at a C:N ratio of 5:1. The drying period prior to amendment with the glucose solution provided conditions for a more significant increase in microbial activity, emphasizing any structural differences which might have evolved between the treatments. Immediately after amendment with the glucose solution, the moisture contents were readjusted to 0.26 g g^{-1} and the samples were placed in mason jars. Gas samples were removed from each jar on a regular basis as in the previous studies over a 20 day incubation period.

RESULTS AND DISCUSSION

Field Study

The relative movement of the wetting front through the respective profiles of the inorganic fertilizer, the low sludge, and the high sludge treatments was used as an indicator of variations in levels of compaction caused by the respective treatments. At all depths, the soil moisture levels at 24 and 48 hours after the water application were essentially the same for each of the treatments, demonstrating that the movement of water through the profile had attained an equilibrium condition after 24 hours. The moisture values before and 24 hours after the water application for March and June are given in Figures 2 through 5. The means of the three replications are plotted on the graphs.

The results from the experiment conducted in March demonstrated a notable difference between the inorganic fertilizer and low sludge treatments and the high sludge treatment at field site 1 (Fig. 2). It was evident that the wetting front penetrated throughout the full profile of the inorganic fertilizer treatment with no apparent restriction to flow. Although the increase in water content for the inorganic fertilizer treatment was only statistically significant ($p=0.05$) through a depth of 80 cm, the trend continued through 105 cm. In contrast, water did not appear to penetrate below 40 cm on the high sludge treatment, with a statistically significant increase occurring at 30 cm only. Note that the ripper used in the field operations penetrated to a maximum depth of 50 cm. Substantial increases in moisture content were recorded at all depths of the low sludge treatment, indicating that the wetting front penetrated

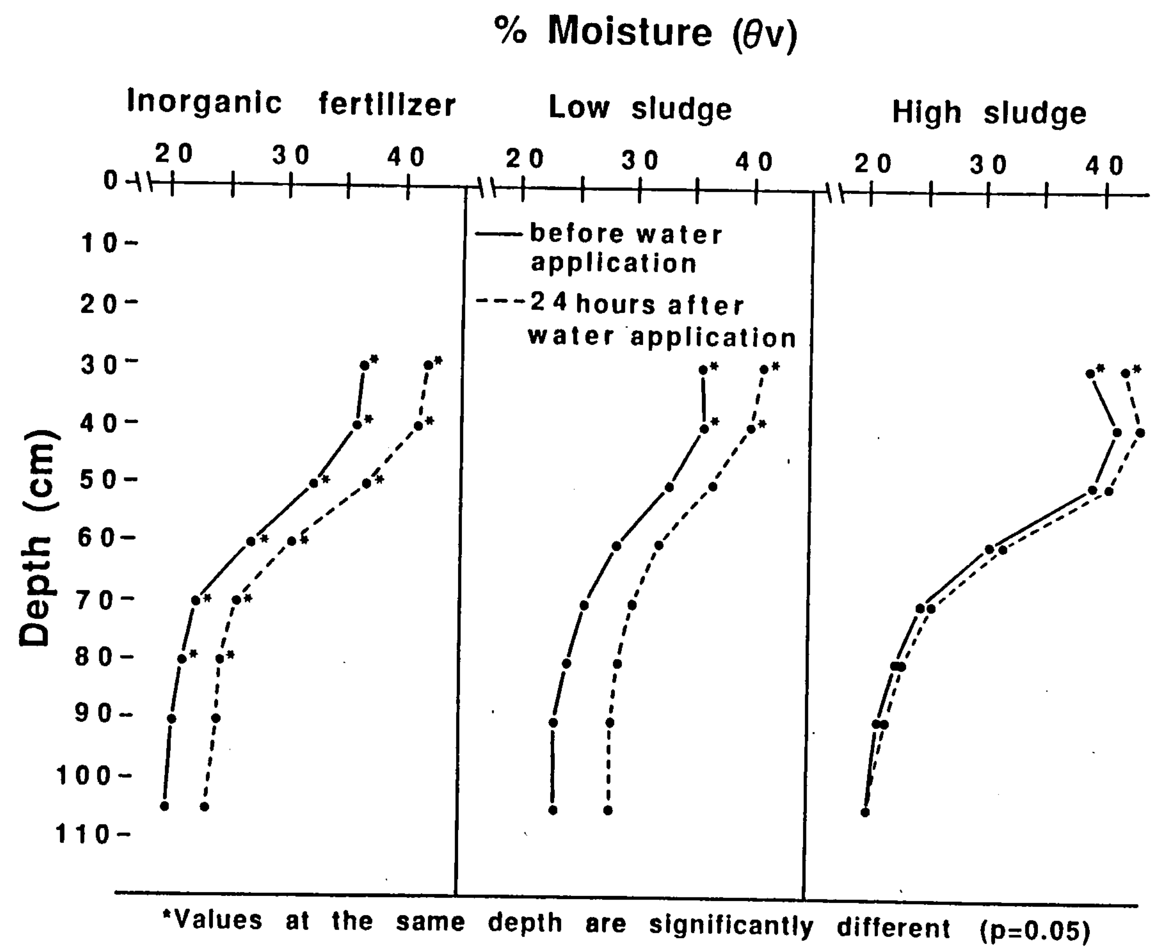


Fig. 2. Soil moisture values measured with the neutron probe at Site 1 in the March field study.

throughout the full profile, although statistically significant increases were only identified at 30 and 40 cm. The results from field site 2 suggested a similar trend, although the differences were not as evident (Fig. 3). Water appeared to have penetrated to 60 cm on the inorganic fertilizer and low sludge treatments, although statistically significant ($p=0.05$) increases were only recorded at 30 and 40 cm depths for the inorganic fertilizer treatment and 30 cm for the low sludge treatment. Water did not penetrate below 40 cm on the high sludge treatment, with a statistically significant increase at 30 cm only. A high degree of variation was found between readings from neutron access tubes within the same bermed area. As a result of the varialbility in the field, substantial increases in moisture content as observed on the low sludge treatment at field site 1 were not always found to be statistically significant. The variability was attributed to spatial variation in the texture and structure of the soil at the site of each neutron access tube.

Substantial differences were also observed between the moisture contents recorded at 105 cm for each treatment at the two field sites. At field site 1 moisture contents of 0.238, 0.283, and 0.205 cm^{-3} cm^{-3} were recorded at 105 cm for the inorganic fertilizer, the low sludge, and the high sludge treatments respectively, while values of 0.297, 0.335, and 0.245 cm^{-3} cm^{-3} were recorded for the same treatments, respectively at field site 2. These data indicate that the high sludge treatment was consistently drier at 105 cm than the other two treatments. The bermed areas received equal amounts of water and the irrigations were consistent for the entire field prior to the experiment, thus the lower moisture

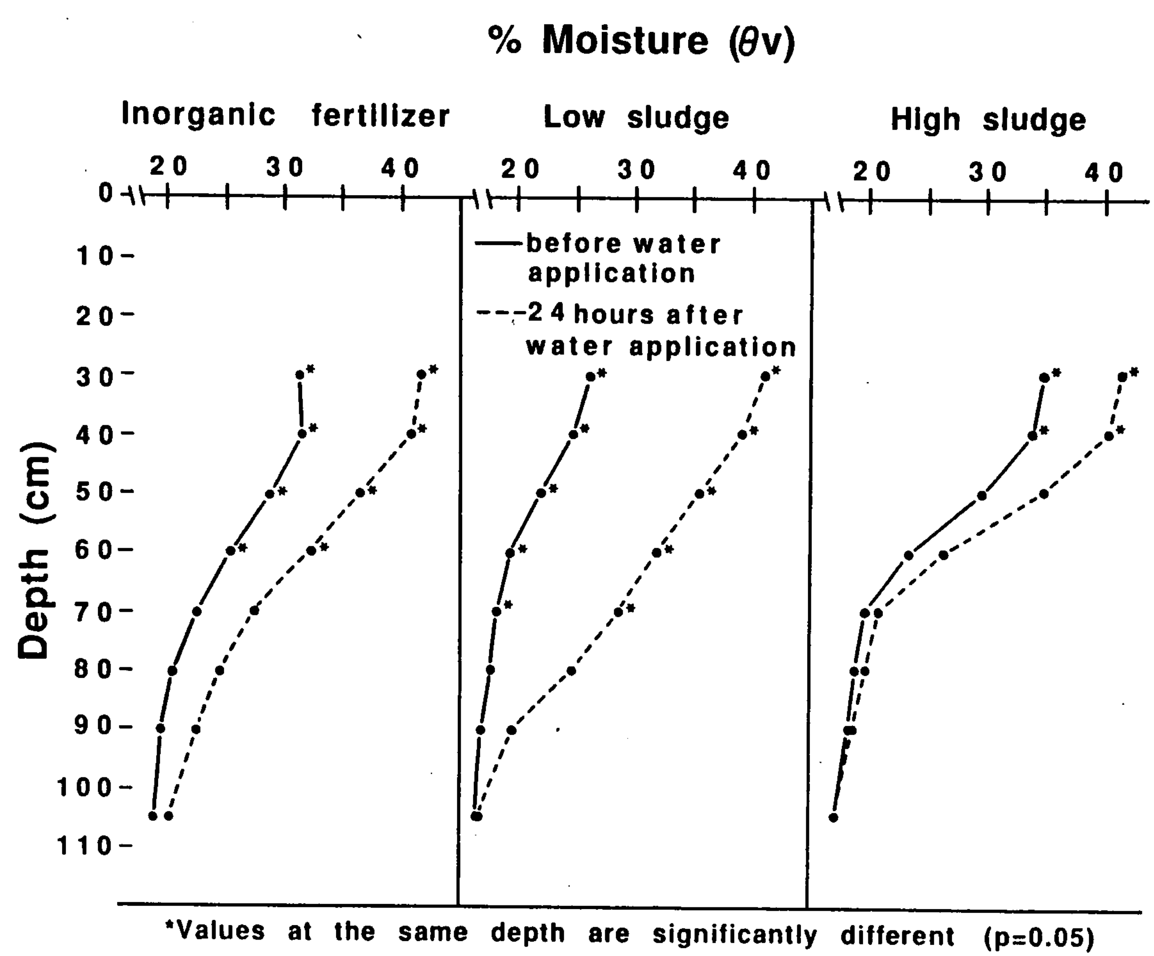


Fig. 3. Soil moisture values measured with the neutron probe at Site 2 in the March field study.

level at the 105 cm depth of the high sludge treatment was indicative of a general restriction of water movement through the soil profile. At both field sites the water infiltration rate at the soil surface, as measured by the speed of absorption of applied water, was more rapid for the high sludge treatment than the other two treatments. Thus the restricted water movement through the profile of the high sludge treatment was not caused by a surface crust, but more likely by a decrease in hydraulic conductivity caused by compaction. In addition, the moisture level of the low sludge treatment at 105 cm was consistently higher than that of both the inorganic fertilizer and high sludge treatments. This data suggested an improvement in soil structure causing an increase in hydraulic conductivity as a result of the sludge amendment.

Repeated sampling of the field at depth intervals down to 120 cm revealed that there was a significant difference in the soil texture of the soil profile at sites 1 and 2 in the field. The change in texture may explain the inconsistencies between the results of treatments at sites 1 and 2. Clay loam soil was found in the top 50-60 cm of the profile throughout the entire field, but the lower portion of the profile was a sandy loam at the first site while that of the second site changed from silty clay to silt loam to sandy clay loam. The depth of the change was inconsisitent, but in general the transition occurred in the region of 50-100 cm. The finer-textured soil in the lower portion of the profiles of treatments at field site 2 would be expected to be more affected by the cumulative compactive forces of field operations from previous years than the coarser-textured soils. Thus a restriction of water movement was observed at 60 cm for all of the treatments at field site 2 causing the impact of the compactive force from the current sludge application to be less significant.

The results of the experiment conducted in June (Figs. 4 and 5) were similar in that the data from field site 1 was more conclusive than that from field site 2. At the first site, an increase in water penetration to a depth of 70 cm was observed for the high sludge treatment as compared with 50 cm in March, but this depth of penetration was still significantly less than the inorganic fertilizer and low sludge treatments where the wetting front moved down through the 90 cm depth. Significant increases ($p=0.05$) in moisture content were only observed to depths of 60 cm on the inorganic fertilizer treatment and 70 cm on the low sludge treatment, although substantial increases were observed in both profiles through depths of 90 cm. As explained previously, the large variation in moisture values obtained from each of the access tubes within a given bermed area reduced the possibility of finding significant differences. Significant increases in moisture content were found at 30 and 40 cm for the high sludge treatment, although the water appeared to have penetrated to 60 cm. The data from field site 2 was inconclusive. It can be seen that the field conditions before the water application were significantly drier in June than in March. The lack of penetration of water through to the bottom portion of the profile on all treatments at field site 2 may have resulted from previous compactive forces as explained above and from compaction due to the shrinking of the clay upon drying during the current growing season. Surface infiltration was significantly influenced by large cracks

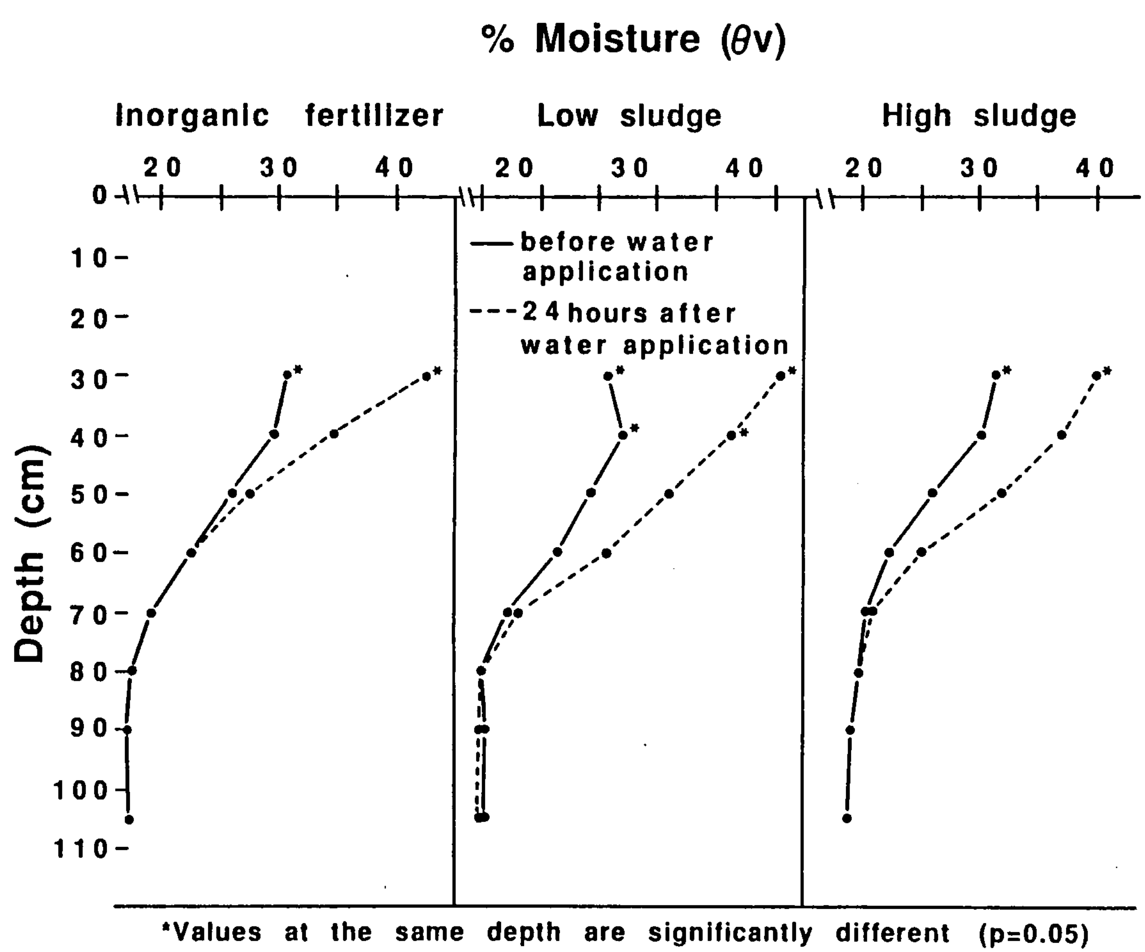


Fig. 4. Soil moisture values measured with the neutron probe at Site 1 in the June field study.

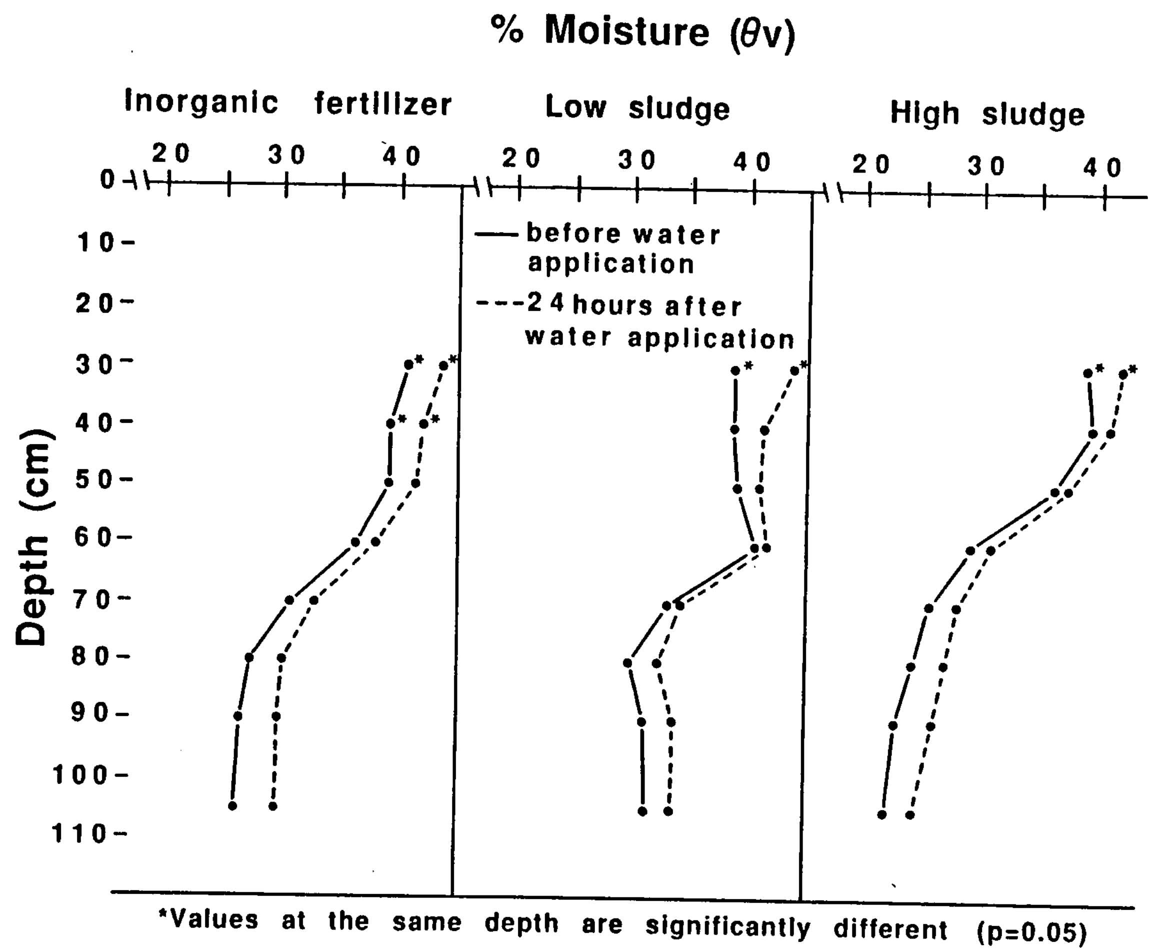


Fig. 5. Soil moisture values measured with the neutron probe at Site 2 in the June field studies.

which had also been created by the shrinking and swelling of the clay loam soil with drying and subsequent irrigations. These cracks conducted water rapidly from the surface to various depths within the profile, thus controlling the infiltration through the upper portion of the profile. The depth of penetration of the cracks was not determined, therefore the degree of influence on the depth of the wetting front could not be specified. The presence of these cracks may explain the penetration of water to 70 cm in the high sludge treatment of field site 1 as opposed to the limited penetration to 50 cm observed in March.

Inspite of the variation observed throughout the field, the results indicated that the high sludge treatment was more compacted than either the inorganic fertilizer or the low sludge treatments. We believe that the depth of the compacted layer differed from 40 to 60 cm for March and June, respectively (based upon the depth of water penetration in the profile), but this variation was probably due to surface cracks caused by shrinking and swelling of the clay soil. Results from both experiments confirmed that the compaction was a subsurface rather than a surface problem.

Laboratory Study

The physical and chemical properties of the Pima clay loam soil are given in Table 1. The soil was a moderately fine textured soil as indicated by the clay content of 31%. The soil texture is highly significant as a controlling factor to soil aeration. At a moisture level of -0.03 MPa, fine-textured soils tend to retain the most water and the

Table 1. Physical and chemical properties of Pima clay

loam soil Soil Property	%
* sand	46
* silt	23
* clay	31
Org C	0.60
Total N	0.06
* Soil Moisture (volume basis)	
-0.03 MPa	28.6
-1.50 MPa	15.2
C:N	10:1
*Bulk density	1.42 Mg m^{-3}
pH	7.8

* Post et al. (1978)

air-capacity falls below 10% of the total soil volume (80% saturation). As explained by Hillel (1982), this contrasts with 25% (38% saturation) or above for sandy soils and between 15 and 20% (57-68% saturation) for loamy soils. However, fine-textured soils with a well-developed structure are characterized by macroaggregates forming a considerable volume of macroscopic (interaggregate) pores which drain quickly, thus providing these soils with an air capacity of 20-30%. Yet, these aggregate structures are readily broken down by compactive forces causing the macropores to disappear and the fine-textured soils to have an air volume of less than 5% (89% saturation). Thus stable structural development provides fine-textured soils with good aeration, but compactive forces can easily destroy the structure leaving a poorly aerated soil at moisture levels close to -0.03 MPa. The level of soil aeration in sandy and loamy soils is primarily a function of the soil texture rather than the structure, thus these soils are less vulnerable to compactive forces.

The soil moisture values at -1.5 and -0.03 MPa as determined by Post et al. (1978) corresponded to values of 0.11 and 0.204 g g^{-1} moisture, respectively. Thus the dry treatments of 0.10 g g^{-1} moisture used in the laboratory studies were representative of the permanent wilting point, while the range of higher moisture values used, represented moisture conditions of field capacity to saturation. The average field bulk density was 1.42 Mg m^{-3} (Post et al, 1978). The percent organic carbon and percent total N were found to be 0.60% and 0.06%, respectively, which are low values normally associated with desert soils. Thus the soil C:N ratio was 10:1 which is typical of humic material. The soil pH as determined from the saturated paste extract was 7.8.

Sludge from the wastewater treatment plant was sampled and analyzed at two separate times (Table 2). Analysis of the sludge filtrate by ion exchange chromatography revealed a negligible concentration of NO_3^--N, indicative of the anaerobic digestion process. Thus the N reported in Table 2 as percent inorganic N consisted of NH_4^+-N, alone. The sludges varied slightly in percent solids, but the low solid content was clearly evident, and necessitated the use of several field applications to apply the high sludge rate. The chemical variation in sludge obtained at different times from the treatment plant was indicative of the inconsistent retention time for the anaerobic digestion of sewage sludge at the treatment plant. The Ina Road treatment plant maintains a simultaneous inflow and outflow of sewage sludge to and from the anaerobic digestor, thus the digestion time for specific sludge is not consistent. The percent organic carbon and N decreased with increased digestion time while the percent inorganic N increased. The overall C:N ratio of the sludge was extremly low, thus microbial decomposition of the sludge would mineralize N rather than immobilize it.

Study 1

The objective of the experiment was to identify the combination of bulk density and moisture content at which soil aeration became limiting to microbial respiration, in a clay loam soil amended with inorganic fertilizer. In all of the treaments, microbial activity was greatest

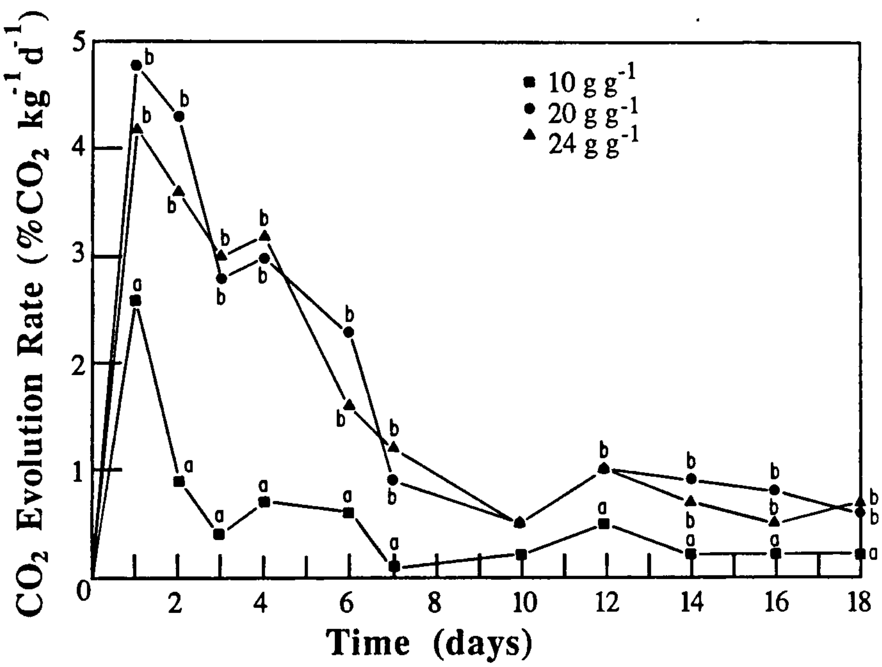
Table 2. Physical and chemical properties of anaerobically digested sewage sludge

	Dry Weight		%		Total Sludge
	solids	Org C	Org N	Inorg N	C:N
Sludge 1 (Study 2&3)	1.6	35.98	5.14	0.097	3.3:1
Sludge 2 (Study 4)	1.5	21.80	4.60	0.118	1.7:1

during the first 24 to 48 hours after the addition of substrate and water amendments. The CO_2 evolution rate then decreased throughout the remainder of the incubation period reaching a steady state after approximately 10 days. This response to added substrate is typical of soil microorganisms. The heterotrophs remain dormant in the soil until supplied with a substrate, which stimulates an initial rapid flux of metabolic activity and growth.

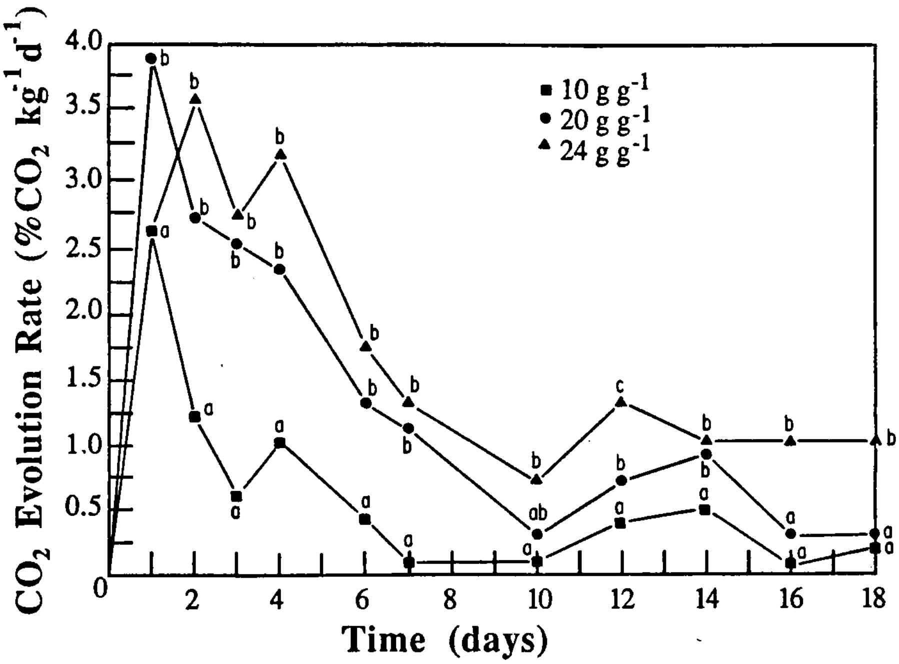
The results in Figure 6 indicate that the CO_2 evolution rate at a 0.10 g g^{-1} moisture content was significantly lower than at moisture contents of 0.20 and 0.24 g g^{-1}, for a soil compressed to a bulk density of 1.1 Mg m^{-3}. It is possible that the limitation to microbial activity was due to a restriction of the diffusion of substrates through the soil to microorganisms due to the low moisture level in the soil. There was no significant difference between CO_2 evolution at 0.20 and 0.24 g g^{-1} moisture. Thus aeration did not limit microbial activity under the moisture levels utilized in this study at a bulk density of 1.1 Mg m^{-3}. Similar results were observed at a bulk density of 1.4 Mg m^{-3} as seen in Figure 7. The CO_2 evolution rate was significantly lower at the 0.10 g g-1 moisture content, but there continued to be no significant difference between CO_2 evolution at 0.20 and 0.24 g g^{-1} moisture.

In contrast, among the soil treatments compacted to 1.6 Mg m^{-3}, the CO_2 evolution rate at 0.24 g g^{-1} moisture was significantly lower than the rate at 0.20 g g^{-1} moisture as seen in Figure 8. At this bulk density, 0.20 and 0.24 g g^{-1} moisture contents correspond to 81% and 97% saturation, respectively. The soils compacted to 1.4 Mg m^{-3} and maintained at 0.24



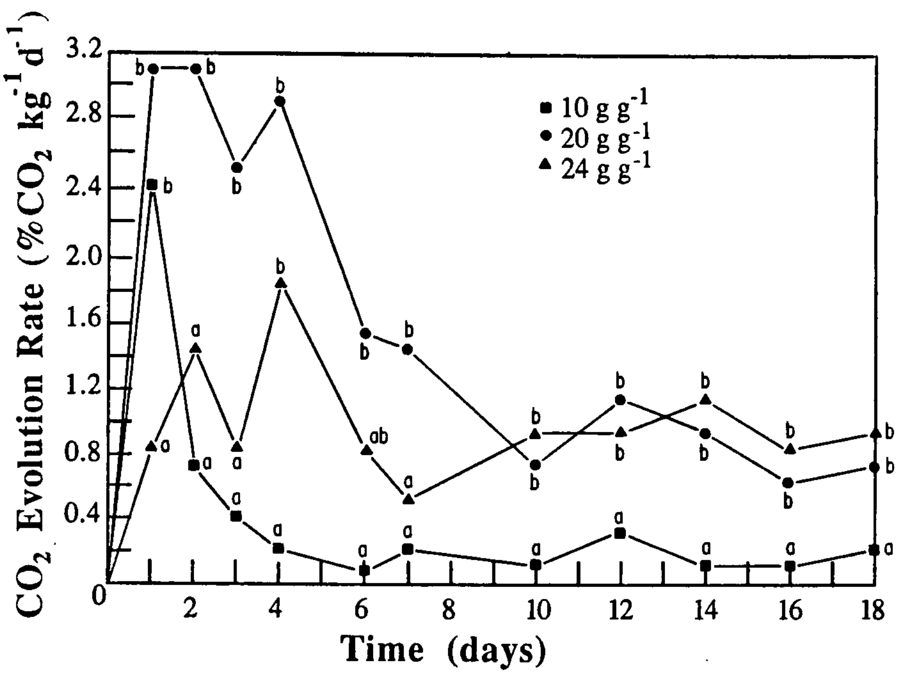
Points with different letters on a given day are significantly different (p=0.05). Corresponding points without letters are not significantly different.

Fig. 6. CO_2 evolution from soils amended with inorganic fertilizer as influenced by moisture contents of 0.10 to 0.24 g g^{-1} at a bulk density of 1.1 Mg m^{-3}.



Points with different letters on a given day are significantly different (p=0.05). Corresponding points without letters are not significantly different.

Fig. 7. CO_2 evolution from soils amended with inorganic fertilizer as influenced by moisture contents of 0.10 to 0.24 g g^{-1} at a bulk density of 1.4 Mg m^{-3}.



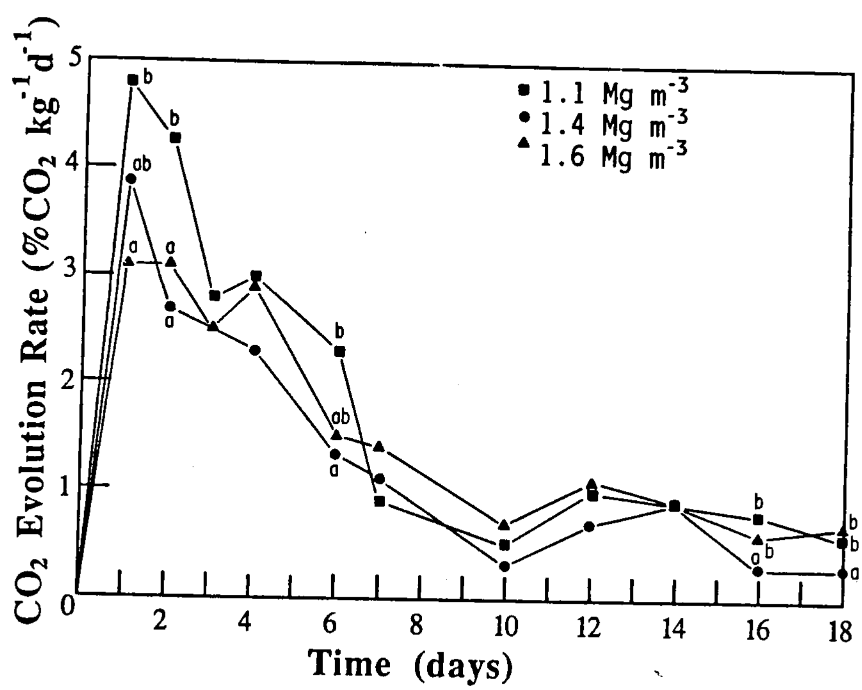
Points with different letters on a given day are significantly different (p=0.05). Corresponding points without letters are not significantly different.

Fig. 8. CO_2 evolution from soils amended with inorganic fertilizer as influenced by moisture contents of 0.10 to 0.24 g g^{-1} at a bulk density of 1.6 Mg m^{-3}.

g g^{-1} moisture had a saturation value of 71%. The CO_2 evolution continued to be significantly lower at 0.10 g g^{-1} moisture.

It was observed that whereas the 0.10 g g^{-1} moisture treatment respiration rates were similar regardless of bulk density, the 0.20 and 0.24 g g^{-1} moisture treatments tended to have reduced respiration rates with increasing bulk density (Figs. 9 and 10). At the 0.20 g g^{-1} moisture level, a significant decrease ($p=0.05$) in the 24 hour CO_2 evolution rate occurred with an increase in bulk density from 1.1 to 1.6 Mg m^{-3}. A similar trend was observed for the bulk densities of 1.1 and 1.4 Mg m^{-3} at the 0.24 g g^{-1} moisture level. These differences were observed during the initial 48 hours when the microbial activity was greatest, after which the differences between the respiration rates of the above treatments were insignificant. Thus the rate of gaseous diffusion of oxygen was only limiting under high levels of microbial activity. In contrast, the CO_2 evolution rate for samples maintained at 0.24 g g^{-1} moisture and compacted to a bulk density of 1.6 Mg m^{-3} remained significantly lower than either the treatment at 1.6 Mg m^{-3} bulk density and 0.20 g g^{-1} moisture or 1.4 Mg m^{-3} bulk density and 0.24 g g^{-1} moisture, throughout the majority of the incubation period. These data demonstrated that the critical point at which aeration significantly restricted microbial activity was at a bulk density of 1.6 Mg m^{-3} and a moisture content of 0.24 g g^{-1}.

The results emphasized the importance of considering water content and bulk density as independent factors affecting soil aeration. Thus limited aeration is a more significant problem in a compacted field when the field is maintained at water tensions close to field capacity. The



Points with different letters on a given day are significantly different (p=0.05).
Corresponding points without letters are not significantly different.

Fig. 9. CO_2 evolution from soils amended with inorganic fertilizer as influenced by bulk densities of 1.1 Mg m^{-3} to 1.6 Mg m^{-3} at 0.20 g g^{-1} moisture content.

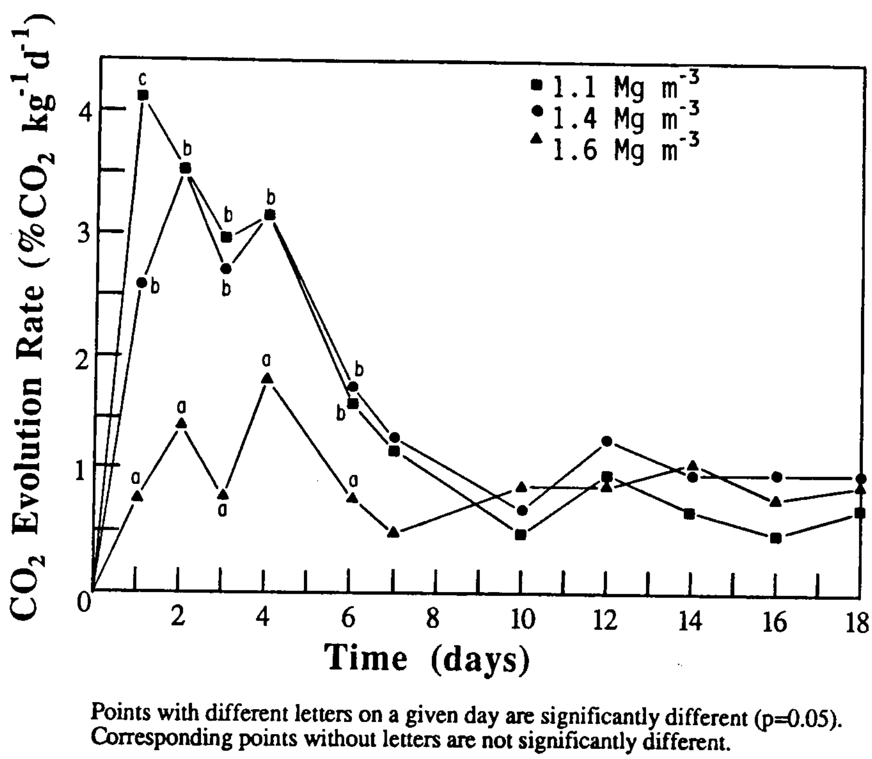


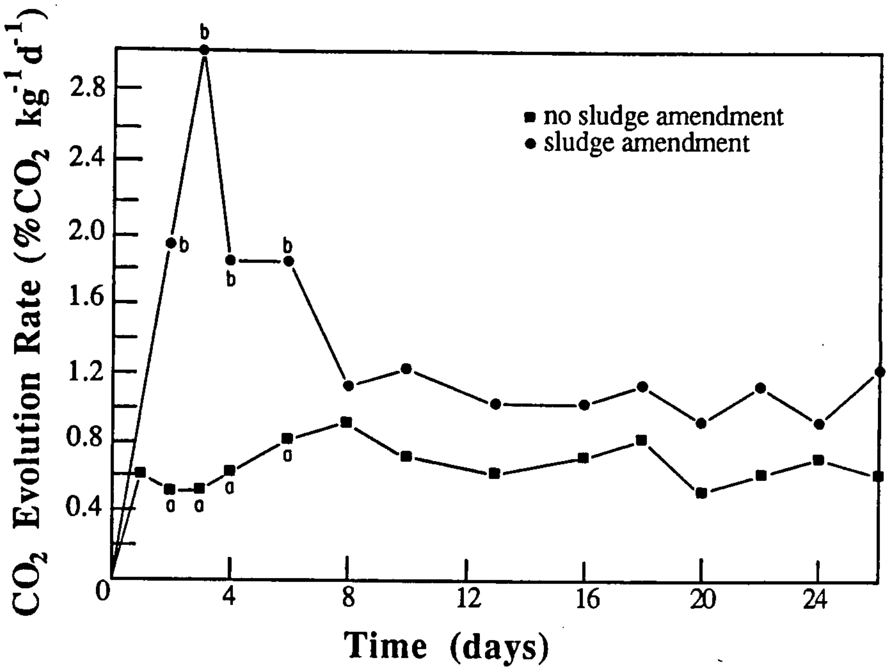
Fig. 10. CO_2 evolution from soils amended with inorganic fertilizer as influenced by bulk densities of 1.1 Mg m^{-3} to 1.6 Mg m^{-3} at 0.24 g g^{-1} moisture content.

results also illustrated the fact that microbial activity was significantly restricted under conditions of low moisture regardless of the bulk density. The above results and the fact that reduced oxygen diffusion did not completely restrict microbial activity until the percent saturation exceeded 80%, differ from the results of Linn and Doran (1984) who identified a specific optimum aeration of 60% saturation. The optimum range identified by this experiment corresponded to 38 to 45% saturation, under conditions of high levels of microbial activity. The decrease in respiration rates observed over the range of 45 to 81% saturation was limited to the time of maximal microbial activity, illustrating the significance of biological respiration rates to soil aeration requirements. A more rapid rate of gaseous diffusion is required to maintain adequate levels of oxygen in soils with high levels of biological activity. The results of this experiment agree more closely with Hillel (1982) who maintained that the range of values for air-filled porosity at which soil aeration was likely to become limiting to root respiration was 5 to 20%, with an average of 10% (75 to 80% saturation depending on the total porosity). Gupta and Larson (1982) also used a value of 10% air-filled porosity as the compaction point below which gaseous exchange with the atmosphere might restrict biological activites.

The sensitivity of microbial respiration as an index of soil aeration was demonstrated by the results. At the critical point where aeration became limiting to microbial respiration, a change in the soil aeration level could be detected over a 4% change in moisture content or a 0.2 Mg m^{-3} change in bulk density. This sensitivity was demonstrated by a comparison of the CO_2 evolution rates at 0.20 and 0.24 g g^{-1} moisture at a bulk density of 1.6 Mg m^{-3} and the rates at 0.24 g g^{-1} moisture for bulk densities of 1.4 and 1.6 Mg m^{-3}.

Study 2 and 3

The major objective of the second and third experiments was to identify the moisture content at which aeration became limiting to microbial respiration in a sludge amended soil compacted to 1.4 Mg m^{-3}. Microbial respiration from a sludge amended soil and a soil with no sludge amendment maintained under the same physical conditions, was also compared to identify the effect of the sludge amendment on the CO_2 evolution rate. The CO_2 evolution rate of sludge amended soil was significantly higher than that of the unamended soil (Fig. 11), when both were compacted to 1.4 Mg m^{-3} and maintained at a 0.24 g g^{-1} moisture content. These results indicated the importance of evaluating the type of soil amendment when measuring soil aeration. Similar microbial activity levels (as indicated by CO_2 evolution rates) were found in soils amended with either inorganic fertilizer or sewage sludge, when maintained at the same bulk density and moisture levels; thus the above results apply to both amendments. The results demonstrate that the presence of soil amendments influences CO_2 concentrations and O_2 requirements in the soil atmosphere, and thus must be considered when evaluating the optimal level of soil aeration in a particular soil. The stimulation of a similar level of microbial activity by both substrates illustrates that N is the nutrient which often limits microbial metabolism in desert soils.

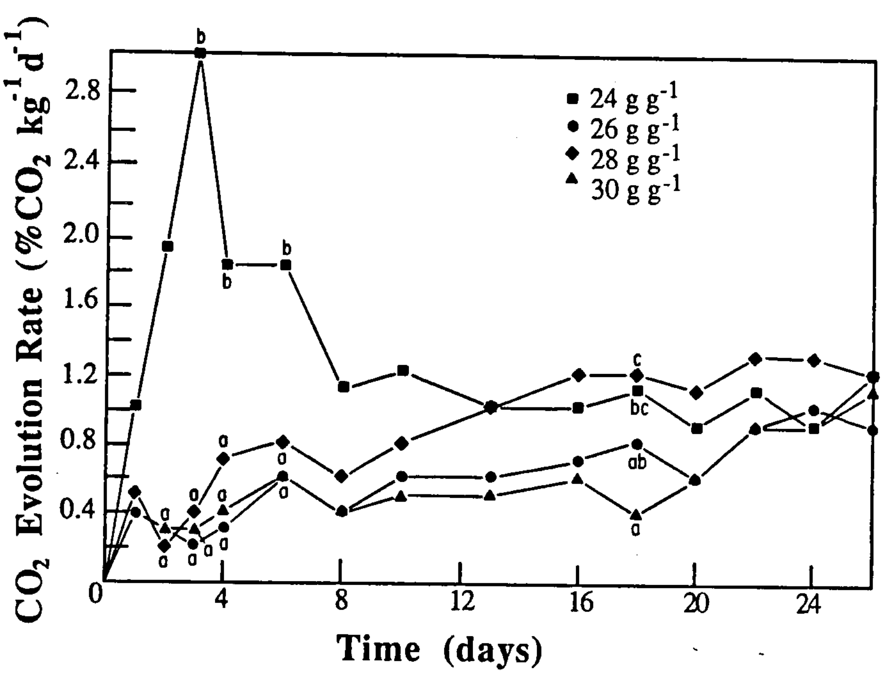


Points with different letters on a given day are significantly different (p=0.05).
Corresponding points without letters are not significantly different.

Fig. 11. CO_2 evolution as influenced by sewage sludge amendment to soil at 1.4 Mg m^{-3} bulk density and 0.24 g g^{-1} moisture content.

The CO_2 evolution rates of soils amended with sewage sludge, compacted to a bulk density of 1.4 Mg m^{-3} and maintained at moisture contents of 0.24 to 0.30 g g^{-1} are shown in Figure 12 (Study 3). It was evident that the respiration rate was significantly lower at 0.26 and 0.30 g g^{-1} moisture than at 0.24 g g^{-1}. Thus a 0.26 g g^{-1} moisture content (77% saturation) in a sludge amended soil compacted to a bulk density of 1.4 Mg m^{-3} was identified as the critical point at which aeration became limiting to microbial respiration. The range of moisture values evaluated in this experiment was determined in a preliminary analysis of sludge amended soils (Study 2) compacted to a bulk density of 1.4 Mg m^{-3} and maintained at a broader range of moisture contents (Appendix 3). The conclusions from Study 3 are confirmed by the data from this preliminary experiment. The data from both experiments demonstrated that a 0.02 g g^{-1} variation in moisture content at the critical point caused a significant decrease in CO_2 evolution. Thus the sensitivity of microbial respiration as an index of soil aeration would have been identified as 0.02 rather than 0.04 g g^{-1} moisture in the first experiment had the intervals been smaller.

The 0.28 g g^{-1} moisture treatment behaved differently. The initial CO_2 evolution rate at 0.28 g g^{-1} moisture was less than that at 0.24 g g^{-1} moisture, and similar to the 0.26 and 0.30 g g^{-1} values. However, by day 13 the 0.28 g g^{-1} treatment was significantly greater than the 0.26 and 0.30 g g^{-1} values. These results could be attributed to the metabolism of a facultatively anaerobic bacterial population exploiting the specific



Points with different letters on a given day are significantly different (p=0.05). Corresponding points without letters are not significantly different.

Fig. 12. CO_2 evolution from sludge amended soils as influenced by moisture contents of 0.24 to 0.30 g g^{-1} at 1.4 Mg m^{-3} bulk density.

level of aeration found at 0.28 g g^{-1} moisture and a bulk density of 1.4 Mg m^{-3}.

It can be noted that in the first study, the critical point at which aeration became limiting to microbial respiration was identified between 0.20 and 0.24 g g^{-1} moisture at a bulk density of 1.6 Mg m^{-3}, corresponding to 81% and 97% saturation, respectively. However, the critical point in this experiment was identified between 0.24 and 0.26 g g^{-1} moisture content at a bulk density of 1.4 Mg m^{-3}, corresponding to 71% and 77% saturation, respectively. As explained above, microbial activity levels were similar for both the inorganic fertilizer and the sludge amendments and thus the variation in amendments could not be responsible for the variation in soil aeration. Therefore, these results emphasize the fundamental limitations of percent saturation as an index characterizing soil aeration. Hillel (1982) defines two limitations to the use of percent saturation as an index. First, the percent saturation is difficult to determine with accuracy due to the methods of sampling available for determining volumetric moisture content and total porosity. A more significant problem exists with the use of percent saturation as an index of soil aeration because the relevant factor is the rate of exchange of soil air rather than simply the content of soil air. In a wet soil, air can be trapped in pockets in the soil from which it is not actively exchanged with the atmosphere, yet this air is still included as part of the total air volume. In the presence of microbial respiration, CO_2 accumulates and O_2 is depleted in such pockets and anaerobic conditions can result. Thus soil aeration must be measured by more dynamic methods as shown by the use of microbial respiration. In addition, the data indicates that the concept of percent saturation was more applicable to a range of moisture contents compacted to a common bulk density, or a range of bulk densities maintained at a single moisture content, than to a general comparison of various moisture levels and bulk densities. The problem associated with the use of percent saturation as a general index was exemplified by the first experiment where the CO_2 evolution rate was higher at 1.6 Mg m^{-3} bulk density and 0.20 g g^{-1} moisture content (81% saturation) than at a bulk density of 1.4 Mg m^{-3} and 0.24 g g^{-1} moisture content (71% saturation).

Study 4

The objective of the fourth experiment was to utilize microbial respiration as an index of soil aeration in order to evaluate the effects of organic and inorganic amendments on soil structure. The amendments used included a low and high sludge application rate, inorganic fertilizer and 0.5% alfalfa. The results of the latter portion of this study were confounded by the growth of fungus of the genus Mucor on the surface of all of the soil samples. The glucose amendment supplied was readily exploited by the fungus which was not outcompeted by soil bacteria as in the previous experiments, when soils were amended with more complex substrates. Since the fungal growth occured on the soil surface, it could not be used as an index of the level of aeration throughout the soil as with aerobic bacteria.

However, the fungal growth did not become prolific until after the sixth day of the incubation period, and in the previous studies, the most significant differences between treatments were seen in the first 6 days of the incubation period. Thus the results from this initial 6-day period were utilized for this study (Table 3). There was no significant difference ($p=0.05$) between any of the treatments, thus indicating that any effect the amendments had on soil structure was minimal. In addition, the limited fungal growth present on a few of the samples during the initial 6 day period increased the variability in CO_2 evolution rates between replicate samples and could explain the lack of significant differences between some of the treatments. During days 2 and 3 of the incubation period, the CO_2 evolution rate from the soil samples treated with sludge at the low application rate was consistently higher than from any of the other treatments including the inorganic fertilizer and the high sludge treatments. The data indicated a possible improvement in soil structure caused by the low sludge amendment. It was evident that the high sludge amendment was less effective than the low sludge amendment, but comparable to the inorganic fertilizer treatment. The lower respiration rates for soils amended with high as opposed to low sludge applications could be a function of toxic substances present in the anaerobically digested liquid sewage sludge, or simply an indication of the difficulty encountered in uniformally incorporating large amounts of liquid sludge into the soil samples. Further research is necessary to confrim the possible positive effects of the low sludge application and

Table 3. A comparison of CO_2 evolution rates from soils at a 0.26 g g^{-1} moisture content and 1.4 Mg m^{-3} bulk density amended with organic and inorganic amendments.

Treatment	CO_2 Evolution Rate ($\%CO_2$ kg^{-1} d^{-1}) Day 1	2	3	4	6
Control	2.67	8.22	10.91	13.38	39.60
Low sludge rate	1.90	10.36	21.47	35.69	58.77
High sludge rate	1.11	4.84	14.06	32.74	67.40
Inorganic	1.48	7.99	14.54	30.86	53.32
0.5% alfalfa	1.25	3.19	12.70	24.48	32.93

to explain the lack of positive effects with high sludge application rates.

Previous work has demonstrated that decreases in soil bulk density were only found with sludge applications equal to or greater than 44.8 Mg ha^{-1} on a dry solids basis (Wei et al., 1985). This level far exceeds the high rate of 7.2 Mg ha^{-1} used for these studies. Liquid sewage sludge must be dewatered in order to utilize such high application rates. The results are in agreement with the conclusions of Somani and Saxena (1975) that organic materials with narrow C:N ratios have a lower impact on the soil bulk density and structural index than materials with high C:N ratios such as wheat straw or rice husks. As seen in Table 2 the C:N ratio of the sludge used for this study was 1.7:1, which is extremely low. Thus the lack of a significant difference between the higher CO_2 evolution rates from soils amended with the low sludge rate and those from the other treatments could be attributed to the following factors: the structural improvement was minimal due to the low application rate (as compared to 44.8 Mg ha^{-1}) or to the low C:N ratio of the sludge, and thus did not significantly affect the level of soil aeration; or the variability caused by the fungal growth reduced the possibility of finding significant differences.

Results from the fifth treatment amended with 0.5% alfalfa were inconclusive. It was observed that the infiltration rate for these soil samples was extremely slow and the moisture retention higher than the other treatments, although the reason is unclear. Thus the soil was 0.5% wetter than the other treatments, since equal amounts of water were added to all samples during the final incubation period. The excess moisture not only reduced the soil aeration level, thus decreasing CO2 evolution, but encouraged more rapid fungal growth. By the first day of the incubation period, fungal growth was evident on one of the replicates of the fifth treatment.

Recommendations For Future Work

Further research is needed for a more complete understanding of some of the relationships observed in these experiments. It was clearly evident from the second and third experiments that a unique population of microorganisms was responsible for CO_2 evolution at a 0.28 g g^{-1} moisture content and a bulk density of 1.4 Mg m^{-3}. In Figures 12 and 15, it was observed that the CO_2 evolution rate decreased significantly at moisture contents in excess of 0.24 g g^{-1}, yet the CO_2 evolution rate from samples maintained at 0.28 g g^{-1} became significantly higher than from those at either 0.26 or 0.30 g g^{-1} moisture during the incubation period. These results suggested that facultatively anaerobic bacteria were stimulated by the conditions of soil aeration present at 0.28 g g^{-1} moisture. This hypothesis could be investigated by supplying selective substrates which would stimulate the specific microbial populations of interest. The evolution of other gases typically generated from the metabolic activity of facultative anaerobes could also be measured. An example would be the N_2O produced by the activity of denitrifying bacteria.

The fourth experiment could also be modified in order to avoid the problems encountered with fungal growth. Amendments would be added and the samples left for a 90 day incubation period following the procedure of the fourth experiment. The soil samples would then be gamma irradiated to eliminate all indigenous microorganisms and reinoculated with a prolific heterotrophic soil bacteria such as Pseudomonas. After amendment with a glucose solution, the respiration rate of the inoculant would be measured as an index of the level of soil aeration in each sample. This procedure eliminates the problem encountered in the present procedure of providing a nonselective substrate, while avoiding extensive surface fungal growth. The above modified procedure would allow for a more complete analysis of the effects of varying sludge application rates on soil aeration. Additional amendments could also be evaluated for the purposes of comparison. Amendment with high application rates of dewatered sludge or materials with high C:N ratios has been reported to cause significant decreases in soil bulk density. Thus the inclusion of additional treatments with the above amendments would provide a better relative comparison of the effect of anaerobically digested liquid sewage sludge on the soil structural index.

SUMMARY

The disposal of anaerobically digested liquid sewage sludge on agricultural lands provides not only a solution to a waste disposal problem, but a source of fertilizer as well. It has been shown that sewage sludge can have an impact on several aspects of soil productivity. Current research has demonstrated that wheat and cotton yields at the University of Arizona's Marana Agricultural Center were comparable for soils amended with either inorganic fertilizer or liquid sewage sludge (A.D. Day, personal communication). It was evident that the sludge provided adequate levels of the essential nutrients to the crops. The present research evaluated the possibility that the sludge further enhanced soil productivity by improving soil physical properties.

The field experiment included high and low sludge treatments and an inorganic fertilizer treatment. The low sludge rate provided nitrogen at a rate comparable to that of the inorganic fertilizer treatment. The high sludge rate was three times that of the low sludge rate and was utilized to evaluate the impact of disposing of larger quantities of waste on a given land area. The higher sludge application rate provided a more economic means of sludge disposal. The experiment monitored water movement through the soil profiles of the respective treatments as an index of the relative structural condition of the soil. It was found that the water consistently penetrated to a greater depth on both the inorganic fertilizer and low sludge treatments, than on the high sludge treatment. The restriction in water penetration on the high sludge treatment was attributed to compaction caused by sludge application methods. As previously explained, three separate sludge applications were required for the high sludge rate due to the liquid nature of the sludge. The clay-loam textured soil did not always dry completely between applications and these moist, fine-textured soils are more readily compacted by the heavy machinery used for sludge applications than coarser textured soils, thus explaining the compaction observed on the high sludge treatment. In addition, the moisture content at a depth of 105 cm was consistently lower for the high sludge treatment than for either of the other treatments, for the experiment conducted in March. This data confirmed the conclusion that there was a restriction in water movement through the profile of the high sludge treatment. In contrast, the moisture content for the low sludge treatment at 105 cm was consistently higher than that of the other treatments suggesting an improvement in the hydraulic conductivity as a result of the sludge amendment.

The laboratory experiments were conducted to determine the moisture content and bulk density at which microbial respiration was restricted by limited soil aeration in soils amended with inorganic fertilizer or liquid sewage sludge. The effect of the soil amendments on soil aeration was evaluated as well. The critical point at which aeration became limiting to microbial activity in the soil amended with inorganic fertilizer was identified at a bulk density of 1.6 Mg m^{-3} and a 0.24 g g^{-1} moisture content. In addition, it was observed that at high rates of microbial activity, the level of soil aeration was optimal at a bulk density of 1.1

Mg m^{-3} and moisture contents of 0.20 to 0.24 g g^{-1}, with increasing bulk densities causing a decrease in respiration rates.

The critical point at which aeration became limiting in sludge amended soils compacted to 1.4 Mg m^{-3} was identified at a moisture content of 0.26 g g^{-1}. As with the soils amended with inorganic fertilizer, the aeration was found to limit microbial activity in the sludge amended soils at levels below the crtical point during the initial 24 hour period of high microbial activity. Over the initial 24 hour period, respiration rates decreased with an increase in moisture content from 0.20 to 0.24 g g^{-1} at the bulk density of 1.4 Mg m^{-3}. It was also found that respiration rates were comparable for soils amended with either sewage sludge or inorganic fertilizer when maintained under the same physical conditions due to the fact that nitrogen was a limiting factor.

In the fourth study, the comparative effects of low and high sludge rate, inorganic fertilizer, and 0.5% alfalfa amendments on soil aeration were evaluated after a 90 day incubation period. The microbial respiration rates were highest for the low sludge rate treatment, indicating a possible improvement in soil aeration as a result of the sludge amendment. The respiration rates for the high sludge treatment were no higher than those of the inorganic control, thus it was evident that a similar structural improvement did not result from the high sludge amendment. This could be a function of toxic substances present in the anaerobically digested liquid sewage sludge or a result of the difficulty encountered with uniformally incorporating large quantities of sludge into the soil samples.

In summary, it was concluded that some degree of compaction was caused by the application of high rates of anaerobically digested liquid sewage sludge using the field operations described. In the laboratory studies, a technique was defined by which microbial respiration was used as an index to identify critical points at which soil aeration became limiting to microbial activity in a specific soil. For Pima clay loam soils, critical points were identified at 1.6 Mg m^{-3} bulk density and 0.24 g g^{-1} moisture content in the soils amended with inorganic fertilizer and at 0.26 g g^{-1} moisture in a sludge amended soil compacted to 1.4 Mg m^{-3}. Using this index, it was found that soil aeration was improved by amendment with low rates of liquid sewage sludge.

APPENDIX 1

As demonstrated by Lindemann et al. (1988) various models have been employed successfully to predict the N-mineralization rate of sewage sludge using decomposition rate constants. The sludge is typically divided into rapidly and slowly decomposing fractions each of which has a separate decomposition constant. The mineralization rate is potentially influenced by soil type, temperature, aeration, and moisture, although Terry et al. (1979) found that soil type, pH, and moisture content (in the range of -.025 to -.1 MPa) had little effect on the sludge decomposition rate. In contrast, the decomposition rate was significantly faster at 30°C than at 21°C over a 56 day incubation period. The rate constants utilized to determine sludge application rates for this experiment were those determined by the Pima-Gro Co. of Tucson, AZ, responsible for the field application of anaerobically digested liquid sewage sludge from the Ina Road Wastewater Treatment Plant. Calculations were based upon the following average characteristics: 8.66% total N; 4.12% organic N; 4.53% inorganic N; a rapidly decomposing fraction of 26.8% organic N with a mineralization rate constant of 0.788; and a slowly decomposing fraction of 65.3% organic N with a rate constant of 0.11. The % N decomposition (% ND) per month for each fraction was determined by the following equation:

$$\%\ \text{ND month-1} = (\%\ \text{organic N})(26.8\%)(0.788) + (\%\ \text{organic})(65.3\%)(0.11)$$

The summation of monthly decomposition values (Σ ND) over the growth period of the crop was added to the available inorganic N to give the plant-available % N from the sewage sludge for the duration of the crop.

APPENDIX 2

The % WFP was calculated using the following equation:

$$\% \text{ WFP} = (\theta_v / TP) (100)$$

where:

$$\theta_v = (\theta_m) (P_B)$$

$$TP = (1 - P_B / P_P) (100)$$

θ_v = percent volumetric water content

θ_m = percent gravimetric water content

P_B = bulk density

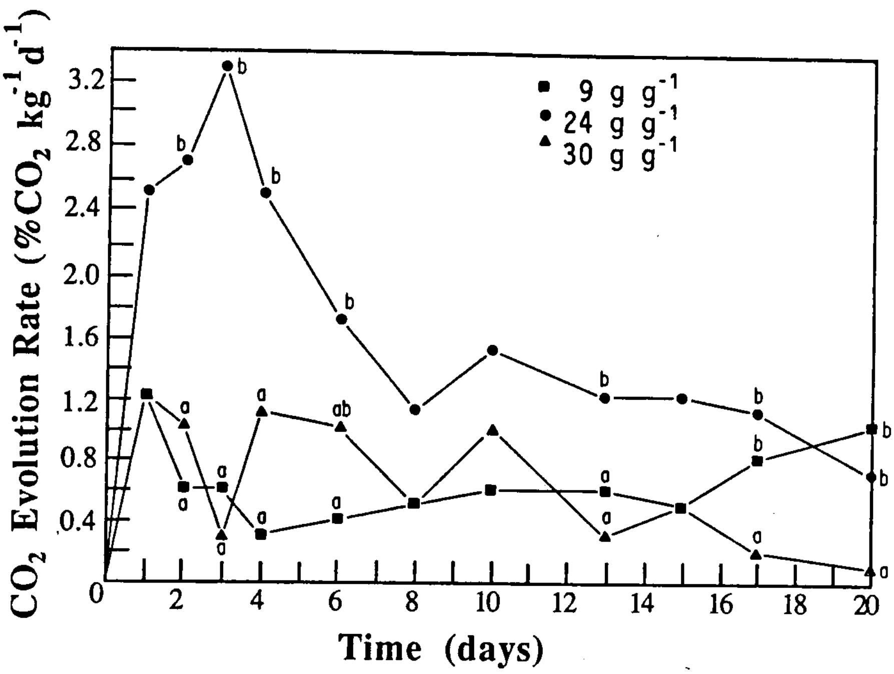
P_P = particle density (assuming P_P = 2.65 Mg m^{-3})

TP = total porosity

APPENDIX 3

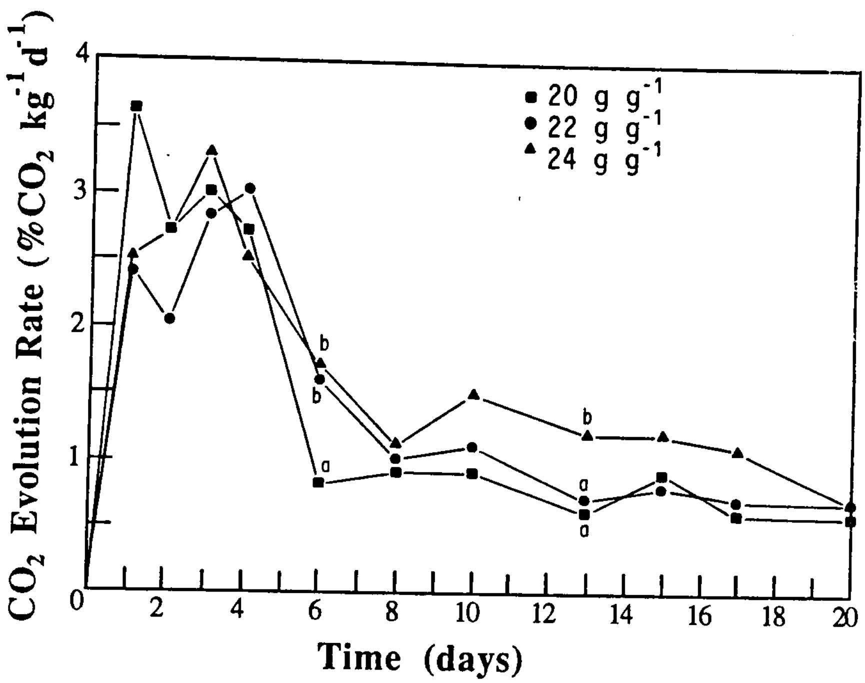
A preliminary experiment was conducted using the Pima clay loam soil, to identify the critical moisture level at which aeration became limiting to a sludge amended soil compacted to a bulk density of 1.4 Mg m^{-3} (Study 2). Moisture levels were maintained from 0.09 to 0.30 g g^{-1}, representing a range from -0.03 to -1.5 MPa. The CO_2 evolution rate was significantly lower at 0.09 and 0.30 g g^{-1} than at 0.24 g g^{-1} moisture (Fig. 13). Figure 14 indicates that there was no significant difference in the CO_2 evolution rates over the range of moisture contents from 0.20 to 0.24 g g^{-1}, as with soils amended with inorganic fertilizer in the first experiment. Yet after 24 hours, a decrease in respiration rate was observed with increasing moisture content from 0.20 to 0.24 g g^{-1} at the bulk density of 1.4 Mg m^{-3}. A similar trend was observed in Study 1 with soils amended with inorganic fertilizer, compacted to 1.4 Mg m^{-3} and maintained at moisture contents of 0.20 and 0.24 g g^{-1} (Fig. 14). As in the first experiment, it was evident that the increase in moisture content sufficiently restricted gaseous diffusion in the soil, to limit soil aeration under high levels of microbial activity. During the remainder of the incubation period, no difference was observed between the respiration rates of 0.20 to 0.24 g g^{-1} moisture levels, indicating that the gaseous diffusion rate in these soil treatments was only limiting to microbial respiration at high levels of microbial activity.

As seen in Figure 15, the CO_2 evolution rate for the sludge amended soil was significantly lower at 0.26 and 0.30 g g^{-1} moisture than at 0.24 g g^{-1}, thus confirming that the critical point at which aeration became limiting to microbial respiration in a sludge amended soil compacted to



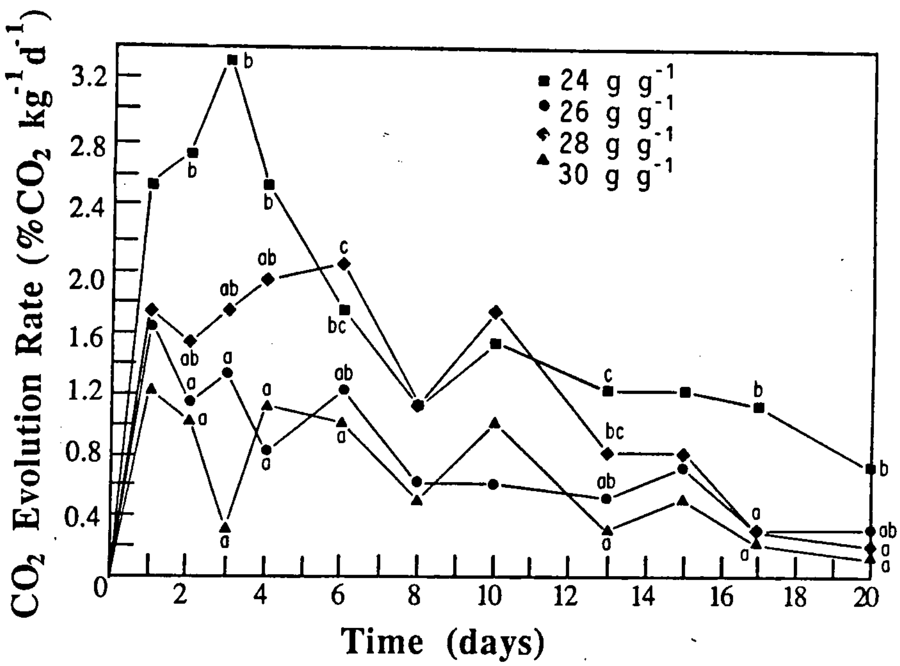
Points with different letters on a given day are significantly different (p=0.05).
Corresponding points without letters are not significantly different.

Fig. 13. CO_2 evolution from sludge amended soils as influenced by moisture contents of 0.09 to 0.30 g g^{-1} at 1.4 Mg m^{-3} bulk density.



Points with different letters on a given day are significantly different (p=0.05).
Corresponding points without letters are not significantly different.

Fig. 14. CO_2 evolution from sludge amended soils as influenced by moisture contents of 0.02 to 0.24 g g^{-1} at 1.4 Mg m^{-3} bulk density.



Points with different letters on a given day are significantly different (p=0.05).
Corresponding points without letters are not significantly different.

Fig. 15. CO_2 evolution from sludge amended soils as influenced by moisture contents of 0.24 to 0.30 g g^{-1} at a bulk density of 1.4 Mg m^{-3}.

1.4 Mg m^{-3} was at a 0.26 g g^{-1} moisture level (77% saturation). In addition the same relationship was observed between the 0.26 and 0.28 g g^{-1} moisture treatments as in Study 3. In a similar trend, the CO_2 evolution rate at 0.28 g g^{-1} moisture was initially lower than the 0.24 g g^{-1} moisture, but similar to the 0.26 and 0.30 g g^{-1} values. By day 6, the 0.28 g g^{-1} value was significantly greater than the 0.26 and 0.30 g g^{-1} values. Thus the data from this experiment confirmed the conclusions stated in the Results and Discussion with respect to Study 3.

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