An Assessment of Cropland Application of Alum Sludge

by

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(ABSTRACT)

Previous research has shown that crop land application of alum sludge can be a valuable method of residuals disposal and has been demonstrated to cause no adverse effects on soil properties and crop yields. Studies have shown that with good soil management practices essential plant macronutrient levels can be maintained to support good crop growth.

This study investigated the application of water treatment residuals in both field studies and greenhouse pot studies in order to determine the effects on soils properties and crop yields. Alum sludge collected from the Blacksburg-Christiansburg-VPI Water Authority and Radford Water Treatment Plant was land applied in the Spring of 1992. Two separate crop rotations, corn followed by wheat, were grown and harvested during the two-year field study. A greenhouse pot study using lettuce and radish plants was initiated in the Spring of 1993.

Soil and plant tissue samples were collected and analyzed for the field and greenhouse studies. Harvest yields were also carefully monitored and recorded. The

results of the laboratory analysis provided information on nutrient concentrations in soil and uptake by plants, and also soil and plant tissue elemental accumulations. Alum and PACl sludge at loading rates of up to 2.5% had no negative impacts on wheat yield. The growth study using lettuce and radish plants concluded that residual additions at low levels improved crop yield and that residual aging prior to land application was essential for good yield.

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Table of Contents

List of Tables

Appendix A

Appendix B

Appendix C

Appendix D

List of Figures

Introduction

The treatment of drinking water from the majority of municipal water treatment plants (WTP's) involves the use of chemical coagulants to enhance the removal of suspended particulates from raw water. The resultant by-product of the coagulation process is an aggregation of raw water impurities and chemical precipitants that, when removed from the water form a solids residual, or sludge. Because of the predominant use of aluminum based coagulants for water treatment in Virginia, aluminum sulfate (alum) and polyaluminum hydroxychloride (PACl) were the coagulants used in this study.

The continuous demand for clean water by the public means that large quantities of sludge are produced. Each treatment plant is responsible for providing a detailed method for sludge disposal which meets EPA approval (Lin and Green, 1987). In the past WTP's were permitted to release sludge into surface waters. However, this form of disposal is being phased out due to the enforcement of the Water Pollution Control Act of 1972 which classified WTP sludge as an industrial waste (Elliott and Singer, 1988). The implementation of this act has resulted in the gradual elimination of direct sludge discharge into surface waters, and forced municipalities to turn to other more costly sludge disposal options. Currently only a small number of disposal options are available for WTP sludge. Some of the more widely used methods are: landfilling, lagooning, discharge into sanitary sewers, and recovery and reuse. Other land application processes include the use of sludge as construction fill and landfill cover, and on forest lands (Lin and Green, 1987).

Lagooning has historically been the most popular WTP sludge disposal option when available land exists on-site at the treatment plant (Doe, 1990). Lagooning is a simple process which incorporates gravity thickening and dewatering. Thickened sludge is stockpiled in lagoons for months or even years of storage at a low cost to the municipality. The problem with lagoons is that they are only a temporary means of disposal. Eventually the lagoons are emptied, so a plan for ultimate disposal must be provided. Some alum sludges are dewatered to only 8-9% dry solids after several years in a lagoon (Doe, 1990). Ultimate disposal from lagoons usually results in dredging, and then landfilling or land applying the WTP sludge.

Disposal to sanitary sewers has been found to work only if there is a nearby wastewater facility that is willing to accept the excess liquid and solid residuals (Cornwell and Westerhoff, 1981). The idea of co-mingling sludges (the process of mixing WTP sludge with wastewater sludge) and then land applying could be a viable alternative in the future. Today this practice is not permitted by law (Doe, 1990).

Landfilling requires that WTP sludges, with initial concentrations of 0.5 - 2% dry solids, be dewatered to a dry solids concentration that complies with landfill regulations (Elliott and Singer, 1988). Landfilling sludge also involves the cost of transportation, labor, and tipping fees. Due to the rapidly decreasing capacity of existing landfills and the difficulty in obtaining new landfill permits, there is now an increasing reluctance to accept WTP sludge at landfill facilities (Elliott and Dempsey, 1991).

One option, currently the focus of research on WTP sludge disposal, is the application of sludge to agricultural land. Land application, compared to the other options, has the potential to be the safest and most economical disposal option. Land applying sludge may offer several advantages over the previously presented disposal options. One advantage is that sludge can be directly applied to land without the expensive process of dewatering necessary for some other disposal options. This alone could greatly decrease overall disposal costs. The WTP sludge could possibly benefit the receiving soil by favorably modifying soil properties and by providing the soil with valuable components recycled in the sludge (Elliott and Dempsey, 1991).

The problem associated with land application of WTP sludge is that there is little available information in the literature on it's long term effects on soils compared to the large amount of research conducted on wastewater treatment plant (WWTP) sludge. Since WWTP sludge contains significant concentrations of valuable nutrients such as nitrogen (N), phosphorus (P), and potassium (K), it is of value for agricultural crop production (Elliott and Dempsey, 1991). The value of WWTP sludge as a fertilizer provided researchers with the incentive to study in-depth the effects of cropland application. The findings of these studies have allowed for state environmental agencies to formulate regulations for land application of WWTP sludge (Elliott and Dempsey, 1991). Because WTP sludge does not have the same fertilizer value, a lesser importance has been placed on land application of the WTP residuals. Only recently, because of the new disposal regulations and higher costs for landfilling, has the interest in WTP sludge land application become a priority. Elliott and Dempsey (1991) concluded that many water utilities in the future will have to change to WTP sludge land application for the primary method of disposal. Before this can be successfully accomplished more information is necessary on the long term effects of WTP sludge on soil and crop growth. There are currently no existing regulations for land disposal of WTP sludge (Doe, 1990).

This research study on land application of sludge looks directly at the effects of alum and PACl sludge on agricultural soils and crops. In order to understand it's effects on soils, a working knowledge of the physical and chemical characteristics of aluminum sludge is necessary. Both, the short and long term effects of land application need to be addressed. This research studies only the short term effects of alum sludge land application. The specific objectives of this research thesis were to:

1. Study the impact of aluminum coagulant sludges (both "fresh" and "aged") on plant growth yields;
2. Determine how sludge additions affect the phosphorus availability to plants in soil;

3. Determine if sludge application affects plant tissue elemental concentrations; and
4. Determine if alum sludge affects soil physical and elemental properties.

Literature Review

Land application as a disposal alternative

Land application of municipal WTP sludge is not a totally new concept. Wastewater treatment plant sludge application has been practiced for many years on agricultural lands due to it's high value as a fertilizer. Land application of WWTP sludge has been demonstrated for years to be cost effective and environmentally safe (EPA, 1983). In 1980 it was reported that one quarter of all WWTP sludge was applied to agricultural lands (EPA, 1983). Today this percentage is much higher.

Compared to WWTP sludge, WTP sludge is of low value as a fertilizer but may be useful as a soil conditioner and liming agent (Elliott et al., 1990). Unlike WTP sludge, WWTP sludge contains significant concentrations of plant nutrients such as N and P, and also valuable micronutrients such as B, Mn, Cu, Mo, and Zn (EPA, 1983). The composition of both WWTP and WTP sludge depends on the source of the raw water being treated. WWTP sludges are known to contain higher concentrations of heavy metals, toxic organics and pathogens that could be harmful to plants and humans. Because of this, WWTP land application programs must be closely monitored to prevent contamination of soils (EPA, 1983).

Land application of alum sludge is typically safer than WWTP sludge because of the low level of contamination of the raw water compared to wastewater (Elliott and Dempsey, 1991). Federal regulations protecting drinking water supplies help to prevent high concentrations of bacteria, metals, and toxic organics that are commonly found in wastewater. Alum sludge is therefore viewed as a relatively inert material with a low potential for causing adverse environmental effects (Elliott and Singer, 1991).

Land disposal of alum sludge has been shown to have less benefits and cause fewer problems compared with WWTP sludge (Dempsey et al., 1989). Land application of alum sludge is in most cases more valuable as a sludge disposal method for WTP's than for it's value to crops (Lin and Green, 1990). Lin and Green (1990) conducted a two year study on corn and soybean crops grown in soil amended with up to 2% dry alum sludge solids per acre of soil (20 dry tons/acre). They concluded from their study that the crops grown with alum sludge amendment showed no significant differences in yield than the control plots. They also showed that nutrient levels, the plant height, grain moisture, and population of the corn and soybeans were not affected. There was no positive or negative effects on soil characteristics and no environmental degradation noted. Because alum sludge application does not negatively affect crop production it is viewed as a feasible disposal alternative (Lin and Green, 1990).

Characteristics of alum sludge

Coagulation and flocculation using aluminum salts such as aluminum sulfate (alum) and polyaluminum chloride (PACl) are widely used in the drinking water treatment process. The addition of coagulant aids such as clay, silica, and organic and inorganic polymers are also common (Lin and Green, 1987). When added to water, aluminum salts typically form aluminum hydroxides ($Al(OH)_3(s)$)which coagulate impurities from the raw water by "sweep floc" coagulation (Amirtharajah and O'Melia, 1990). This process is a combination of particle destabilization and then adsorption of particles to the flocs. As the hydroxide solids flocculate and then settle to the bottom of the settling basin, particles in the water are enmeshed in the hydroxide matrix and are thus removed. The settling process leaves behind a solids residual that is typically 98.5-99% water (Lin and Green, 1987).

The components of alum sludge vary according to the raw water quality and chemical additions used for treatment. Typical constituents are metal hydroxides; solids such as clay, silt, and silica; and a low concentration of trace metals and organics (Elliott et al., 1990). Nitrogen and phosphorus concentrations are dependent upon the raw water source and the nature of additional chemicals added during treatment. Alum sludge has been shown to contain a total Kjeldahl nitrogen concentration of up to 1%. (Elliott and Dempsey, 1991; Rengasamy et al., 1980; Lin et al., 1988).

The aluminum concentration in WTP sludge is typically 5 - 15% of the total dry solids, which is 50 -100% higher than the concentration of Al in most soils (Elliott and Dempsey, 1991). Elliott and Dempsey (1991) determined that at a 10 ton/acre loading rate with a sludge Al concentration of 30%, the soil Al level was reported to only increase by 0.3%. Aluminum phytotoxicity is dependent on Al solubility and is not problem as long as the pH range in soils is maintained between 6-6.5 (Elliott and Dempsey, 1991).

The problems associated with alum sludge are the formation of metal hydroxides and the possibility of increasing trace metal concentrations. Hydrous oxides are known to strongly adsorb trace metals and dissolved organic matter (Elliott and Dempsey, 1991). Metal hydroxides when added to soil have both a positive and negative effect. They can be beneficial in improving soil chemical characteristics by adsorbing trace toxic metals from the soil, while on the other hand, hydroxides may cause metal deficiencies by binding soluble phosphorus in soils (Elliott and Dempsey, 1991).

Trace metals in WTP sludge are typically low and show no known toxic effects to soil microorganisms. Elliott et al. (1990) showed the concentrations of chromium and nickel in WTP sludge to be equal to normal soil levels, while the copper, lead, and zinc concentrations were found to be three times less than normal soil levels. They concluded that the sludge loading rates for land application would typically have no effect on the overall soil metals concentrations. However, this depends on the specific constituents found in the sludge. Where copper sulfate is used for algae control in raw water sources, high copper levels can be expected in soils receiving these sludges. The mobility of metals in the soil is also a concern for WTP sludge application. Knocke et al. (1991) concluded that metals movement in sludge amended soils was not related to sludge loading but was controlled only by soil pH.

Sludge toxicity to soil microorganisms was also a cause for concern. In order to investigate potential sludge toxicity, Dempsey et al. (1990) conducted microtox tests using WTP alum sludge on Pseudomonas fluorescens, a prevalent soil microorganism. From this study it was determined that alum sludge toxicity to soil microorganisms was negligible.

Metal uptake by plants growing on sludge amended soils has also been an issue of environmental concern. Lin et al. (1988) found no significant increase in the concentrations of nine metals in corn and soybean leaf tissues that were raised in sludge amended soil. Knocke et al. (1991) reported that certain metals, such as Cu and Mn, did in fact increase in the tissues of tall fescue as a result of WTP sludge addition; however, the metal concentrations were well below levels deemed limiting to plant growth.

Effects of alum sludge on phosphorus availability

Phosphorus is one of most important nutrients necessary for plant growth in both soils and water. In many soils P is infact the nutrient that limits plant growth. Phosphorus in soils can be classified into three categories; soluble P, loosely sorbed or labile P, and fixed P (Elliott and Dempsey, 1991). Most plants can successfully utilize the soluble P and the labile P fractions; however, the fixed P cannot be readily used.

Alum sludge, when added to soil, is known to strongly adsorb inorganic P (Elliott and Dempsey, 1991). Metal hydroxide application to soil does not change the total P concentration in soil, but it does affect the ability of plants to extract P from the soil matrix (Elliott and Dempsey, 1991). Tests conducted by Rengasamy et al. (1980) and Elliott and Singer (1988) demonstrated a reduced P uptake in the tissue analysis of maize and tomato shoots, respectively, grown in WTP alum sludge. Knocke et al. (1990) grew tall fescue on alum sludge amended soil and saw a 6% decrease in growth for each 1% increase in sludge addition. The authors concluded that the decreased yield was due to P deficiency in the fescue tissue. Also, they concluded that the impacts of sludge on yield can be negated with P fertilization. Likewise, Elliott et al. (1990) suggested that land application of WTP sludge should not be rejected due to P binding concerns because fertilization can be utilized to remedy the P loss to hydroxide binding. With good soil management and crop selection, P depletion can be prevented (Elliott et al., 1990). In some cases, such as soils that are over fertilized with P, Al sludge can be applied to reduce the soluble P and prevent the problem of phosphorus runoff into receiving surface or groundwater (Dempsey et al., 1989).

Alum sludge effects on soil physical properties

Alum sludge is considered to have potential for soil conditioning. Soil conditioning refers to the modification of soil physical properties by addition of agents that increase bulk density. Bulk density is a measure of the soil porosity. A high bulk density means that the soil is more compact with less pore space. This is unfavorable for plant growth because of increased mechanical resistance to root penetration. A low bulk density (less compacted soil) has more pore space for air and water which is beneficial to plant growth (Tisdale and Nelson, 1975). Rengasamy et al. (1980) found that soil mixed with alum sludge increased soil aggregation and moisture retention and, as a result, increased the dry yield of maize (Zea mays).

Alum sludge is viewed as a useful type of soil bulking agent for certain soils. The hydroxides contained in the alum sludge are known to flocculate the clay, sand, and silt particles in the soil. Upon dehydration, the hydroxides act as a cementing agent which physically binds the soil particles into small, stable aggregates (Elliott and Dempsey, 1991). These aggregates improve soil structure by producing both large pores for gas transfer and small pores for water retention. This soil structure is considered ideal for crop growth and erosion prevention. (Elliott and Dempsey, 1991). Bugbee and Frink (1985) demonstrated that improvements in soil aeration and moisture retention promoted by the addition of alum sludge were able to offset the phosphorus deficiency in lettuce. Because of this an increase in dry weight yield was seen in lettuce grown in sludge amended pots.

Organic matter in WTP sludge has little effect on soil conditioning. An average value of 3% total organic matter in WTP alum sludge was reported by Elliott et al. (1990). This value is much lower than the organic content in WWTP sludges. WTP alum sludge at a loading rate of 2% dry alum sludge solids per acre of soil (20 dry tons/acre) was loaded onto agricultural cropland with no increase on soil organic concentration or soil moisture content (Lin and Green, 1987).

Summary

Land application can be a safe and cost effective means for alum sludge disposal. Due to the variable characteristics of different raw water sources, allowable sludge application rates must be considered according to each individual sludge composition. The problems associated with land application are due to the presence of heavy metals and the potential for phosphorus binding. Research studies have demonstrated that with a proper management program, including P fertilization and metal application limits, land application can be successful.

Previous Research at the Field Site

Introduction

A field study to assess the effects of cropland application of water treatment plant aluminum sludge (alum and PACl) was initiated in the Spring of 1992. A small section of land at the VPI&SU Research Farm in Whitethorne, Virginia was used in the study.

The goal of the first phase of the land application study was to monitor the effects of aluminum based water treatment residuals on soil and corn tissue elemental properties, and to determine how corn yields would be impacted by sludge additions. This section of the report contains background information on the field study experimental design and methods, as well as a brief summary of the results obtained. A more complete analysis of the first phase of the American Water Works Association Research Foundation (AWWARF) crop land application study can be found in, "An Assessment of Cropland Application of Water Treatment Residuals", by Novak et al., 1993.

Sludge characterization

The water treatment plant residuals used in the field study were supplied by the Blacksburg-Christiansburg-VPI Water Authority (Montgomery County, Va.) and the Radford Water Treatment Plant (Radford, Va.). The treatment plants use the

New River as their sole raw water source. Both facilities use coagulation, settling and filtration for raw water treatment. The Blacksburg plant uses an inorganic PACl for coagulation while the Radford plant uses alum along with small amounts of powdered activated carbon (PAC). The PACl and alum sludge used in the study were removed from the sludge holding lagoons located onsite at each treatment plant. The sludge solids were transported to the experimental research site at the VPI&SU Research Farm in Whitethorne, Va..

Alum and PACl sludge samples were collected from their respective treatment plants in February, 1992 and a chemical characterization was performed on each sludge. Results from the sludge characterization analysis are presented in Table 1. The tests conducted included elemental metals analysis, TKN, EPC, % solids, pH, ammonia, nitrate, nitrite and total aluminum. TCLP tests were used to determine the ability of toxic sludge constituents to be leached from the sludge matrix. These elemental constituents consist of Cd, Cr, Pb, As, Se, Ag, Ba, Hg, and Al. An Inductively Coupled Argon Plasma Emmission Simultaneous Spectrophotometer (ICP) was used for analysis of these elements.

Field study soil analysis

Soil samples were collected from the experimental field site at the VPI&SU Research Farm and analyzed in order to determine soil chemical and physical properties. Tests conducted included elemental analysis, equilibrium phosphorus

Table 1

Analysis of alum and PACl water treatment plant residuals.

Parameter	Sludge Type PACl	 Alum
% solids	1.5	3.75
pH	6.1	5.5
TKN	11,000	4,760
Inorganic N	2	12.2
Ammonia	86.5	51
P	6.5	0
K	79.3	50.9
Ca	842	851
Mg	104	87.2
Na	62.5	50.5
S	104	93.6
Zn	8.1	4.6
Mn	196	758
Cu	6.2	2.8
Fe	203	190
Al	2,330	6,350
Total Al (6N HCl)	3,710	9,740
B	0	0
Cd	0.03	0.02
Cr	0.2	4.2

Notes: All values, except pH and % solids, are expressed as mg/kg. pH and % solids are dimensionless. All metal concentrations, except as noted, are based upon Mehlich 3 extraction procedures.

concentration, pH, particle size analysis, and the cation exchange capacity (CEC) (Novak et al., 1993). Appendix A contains the results of the field soil physical and chemical analysis.

Crop land application of WTP residuals

The WTP residuals were transported in liquid slurry form by a tank truck to the VPI&SU Research Farm site in April, 1992. The experimental plots were located on a level section of the farmland adjacent to the New River. The soil at this site is considered to be prime farmland. The experimental plot setup consisted of twenty plots, each of which were 6.1 m wide by 12.2 m long with a 1.5 m between plots and a 4.6 m border strip surrounding the entire plot matrix. Fabric aprons were constructed around each sludge plot to contain the wet sludge while dewatering, and also to prevent the alum and PACl sludges from mixing together. The sludge was allowed to dewater and was then mechanically incorporated into the soil (Novak et al., 1993).

Experimental Design

The experimental design used was a randomized complete block matrix using four replications of each sludge application rate. The four application conditions were:

1. Control - no residuals added.
2. PACl at a loading rate of 1.5% by dry weight (*15 dry tons/acre).
3. PACl at a loading rate of 2.53% by dry weight (*25.3 dry tons/acre).
4. Alum at a loading rate of 1.34% by dry weight (*13.4 dry tons/acre).

*Acre furrow slice method.

Conventional farming and soil management practices for growing corn were used for the study. The soil for the entire area of the block was fertilized with 90 kg/ha of phosphorus and 112 kg/ha of nitrogen in the form of diammonium phosphate (DAP). Weed control herbicides were also added prior to the first crop application (Novak et al., 1993)

Crop history of field site

Sludge applications, dewatering and cultivation of the field plots at the VPI&SU Research Farm was completed in April of 1992. The entire block was seeded with corn (Southern States 844V), on June 13, 1992, at a density of 24,000 seeds per acre. The corn crop was harvested in September of 1992 (Novak at al., 1993). After the corn was removed the plots were prepared for seeding with soft red winter wheat (FFR 555).

Summary of background research

Corn leaf tissue was collected from the field plots prior to plant pollination in order to perform a tissue elemental analysis. A statistical analysis for the leaf tissue elemental data for each sludge treatment is presented in Table 2. Leaf tissue P was found to be highest in the PACl (2x) treated plots. Both of the PACl treated plots had tissue P levels significantly higher than the alum treated plots. Tissue zinc concentrations for the PACl treatments were found to be significantly higher than the control plots. The tissue Zn concentrations in the alum treated plots were not significantly different from the control plots. Nitrogen levels in the corn leaf tissue were within acceptable ranges to support good grain yield (Novak et al., 1993).

While corn plant samples were collected from the field plots at harvest and analyzed for tissue elemental content. A summary of the statistical analysis for the tissue elemental data is presented in Table 3. Tissue P concentrations were found to be significantly higher in the control plots as compared with the sludge treated plots. Tissue N concentrations for the control, PACl (1x) and the alum treated plots showed no significant differences amongst each other, however, the control plot tissue N was significantly higher than the PACl (2x) treated plot tissue (Novak et al., 1993). Corn tissue potassium levels were found to be at the highest concentrations in the control, PACl (1x) and alum treated plots. The K concentration in the PACl (2x) treated plots was significantly lower than the other plots which received sludge additions (Novak et al., 1993).

Table 2

Elemental analysis of corn leaf tissue collected at anthesis from WTR treated field plots.

Loading	P	K	N	Ca	Mg	Al	Zn	Mn	Fe	Cu	B	S
	%						ppm					
Control	.24 ab*	1.15 ab	2.85 a	.43 ab	.36 a	17.2 a	10.0 c	36.1 a	51.5 a	1.89 a	3.77 a	493 a
PACl (1x)	.24 ab	1.51 ab	2.84 a	.37 ab	.30 ab	23.8 a	14.2 b	47.4 a	56.0 a	2.47 a	4.01 a	356 a
PACl (2x)	.26 a	1.12 ab	2.61 b	.51 a	.39 a	17.6 a	17.7 a	39.5 a	57.5 a	2.48 a	4.16 a	514 a
Alum A	.21 c	1.60 a	2.71 ab	.34 b	.24 b	23.5 a	12.5 bc	39.9 a	53.1 a	2.32 a	4.53 a	518 a

* Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

Source: Novak et al., 1993.

Table 3

Elemental analysis of corn plant tissue collected at harvest from WTR treated field plots.

Loading	P	K	N	Ca	Mg	Al	Zn	Mn	Fe	Cu	B	S
	%					ppm						
Control	.16 a*	.78 ab	1.22 a	.50 a	.43 a	19.6 abc	14.2 a	51.8 a	40.5 a	4.1 a	4.23 a	671 a
PACl (1x)	.13 b	.97 a	1.7 ab	.44 ab	.35 ab	25.2 a	14.2 a	52.3 a	40.3 a	3.2 ab	3.23 a	538 a
PACl (2x)	.13 b	.62 b	1.04 b	.44 ab	.41 a	15.1 c	16.7 a	37.0 ab	32.0 b	2.5 b	2.74 a	559 a
Alum A	.12 b	1.03 a	1.15 ab	.39 b	.28 b	22.1 ab	14.4 a	52.3 a	35.7 ab	2.6 b	3.20 a	641 a

* Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

Source: Novak et al., 1993.

A statistical analysis of the corn kernel elemental data (Table 4) demonstrated that all of the elements analyzed, with the exception of Zn, were not significantly different. The kernel tissue Zn concentration was found to be significantly lower in the PACl (2x) treated plots (Novak et al., 1993). Results and statistical analysis of the corn gram yield data is presented in Table 5.

Corn grain yields at harvest showed no significant differences for the different sludge treatments. The crop yield for all treatments was considered to be above average (Novak et al., 1993).

Table 4

Elemental analysis of corn kernels harvested from WTR treated field plots.

Loading	P	K	N	Ca	Mg	Al	Zn	Mn	Fe	Cu	B	S
			%						ppm			
Control	.28 a*	.39 a	1.28 a	.53 a	.12 a	10.4 a	18.1 a	5.6 a	23.4 a	9.3 a	1.3 a	521 a
PACl (1x)	.28 a	.39 a	1.14 a	.63 a	.13 a	12.3 a	19.7 a	6.7 a	22.5 a	6.5 a	1.7 a	589 a
PACl (2x)	.34 a	.47 a	1.26 a	.68 a	.14 a	10.7 a	26.1 b	7.1 a	23.4 a	6.4 a	1.6 a	466 a
Alum A	.32 a	.44 a	1.31 a	.59 a	.13 a	14.2 a	20.1 a	7.0 a	25.1 a	6.0 a	1.8 a	616 a

* Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

Source: Novak et al., 1993.

Table 5

Grain yield of corn harvested from WTR treated field plots.

Loading	kg/ha	Crop yield** (Bu/A @ 12% moisture)
Control	9,601 a*	168 a
PACl (1x)	8,399 a	139 a
PACl (2x)	8,940 a	151 a
Alum	9,473 a	160 a

* Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

**Replicate crop yield data

Plot No.	Control	PACl (1x)	PACl (2x)	Alum
1	155.0	171.1	119.9	153.0
2	190.8	143.0	148.8	178.3
3	155.5	108.7	198.5	178.8
4	172.6	134.9	136.7	131.3
Mean	168	139	151	160
Standard Deviation	17.0	25.7	33.8	22.8

(Novak et al. 1993)

Experimental Methods and Materials

Wheat field experimental design

Existing field site

The existing field research site at the VPI&SU Research Farm was used for the second phase of the WTP cropland application study. The plot layout and residual loading rates were identical to the first phase of the study. The only addition to the field plots prior to the planting of winter wheat in October, of 1992, was an application of nitrogen and potassium fertilizer.

Winter wheat application

After the corn crop harvest in the fall of 1992, the field plots were prepared for planting soft red winter wheat (FFR-555-N). The soil was tilled and fertilization was applied at 22 kg/ha of nitrogen and 135 kg/ha of potassium. A Haybuster no-till drill was used to plant wheat at a seeding rate of 112 kg/ha. On April 15, 1993, a second N addition of 90 kg/ha was applied.

Data collection

Soil sampling

Soil samples were collected from the field plots prior to wheat growth. Six soil samples, approximately 10.2 cm to 15.2 cm deep, were randomly collected within each plot using a Hoffer soil sampler. The samples were pooled together into a bucket and thoroughly mixed. A 75 g subsample of this larger sample was used for later elemental analysis. Soil samples were air dried for about one week to eliminate soil moisture and passed through a 2 mm sieve to remove unwanted material and provide soil size uniformity. The samples were later analyzed for equilibrium phosphorus concentration (EPC) and total kjeldahl nitrogen (TKN) at the VPI&SU Environmental Engineering Laboratory. The remaining soil samples were sent to the Virginia Tech Soil Testing Laboratory for a complete elemental analysis. The Soil Testing Lab analyzed soil samples for concentrations of Mn, Zn, Cu, S, Mg, Fe, K, Ca, P, and Na. (See experimental methods section on methods of soil analysis) Soil samples were again collected after the wheat harvest using the same sampling method and chemical analysis procedures.

Tissue sampling

Wheat tissue samples were collected from each plot at plant anthesis on April 19, 1993, to determine metals and nutrient content. Anthesis is the stage in wheat growth just prior to wheat head formation and pollination. Anthesis occurs approximately during the middle of the wheat growth cycle. Ten whole wheat leaves were cut from randomly selected plants within each plot. Samples were oven dried at 70°C for 24 hours and then ground into a fine powder for later chemical analysis.

On July 12, 1993, wheat leaf and whole plant samples were collected. Before the grain harvest, 15-20 wheat leaf samples were cut from randomly selected plants within each plot. At the same time approximately 15-20 whole wheat plants were randomly collected from the plots to assess dry weight yield, metal accumulation, and nutrient deficiency. The total weight for each wheat plant was recorded. The seeds, stems, and heads were then hand separated and weighed to determine wheat component yields. The component samples were oven dried at 70°C for 24 hours and ground into a fine powder for later analysis. An elemental analysis using the Nitric-Perchloric Acid Digestion method (APHA, AWWA, WPCF, 1992) was performed on the stems and seeds. (See the experimental methods section on tissue elemental analysis.)

Total plant biomass samples were obtained by cutting and collecting all of the plants in a 1.5 m x 0.76 m section on each plot. The samples were placed in cloth harvest bags and dried at 70°C for 24 hours. The dry weight of the biomass was then determined and used to calculate the total biomass yield per plot.

Grain harvest

The wheat field plots were harvested on July 14, 1993. The grain was mechanically harvested using a small plot Winterstieger harvester. The grain was collected from a 1.3 m x 10 m sectional area in each plot. Grain was then analyzed using a portable moisture meter to determine the percent moisture and test weight for each field plot. The total grain yield per plot was calculated using the moisture and test weight values.

The wheat grain was ground into a fine powder and oven dried at 70°C for 24 hours. Grain was then analyzed for tissue elemental concentrations by the Nitric-Perchloric Acid Digestion method (APHA, AWWA, WPCF, 1992).

Methods of chemical analysis

Method for equilibrium phosphorus concentration

The EPC is a measure of the ability of soil to adsorb phosphorus. The EPC analytical method requires 2.5 grams of soil to be shaken with 25 mL of 0.01 M $CaCl_2$ in a plastic centrifuge tube. The tubes were then hand shaken for 45 seconds in order to extract the soluble P from the soil matrix. The solution was then centrifuged at 3000 rpm for three minutes at 20°C, and the liquid decantant was separated into a polyethylene bottle. Two drops of chloroform were added to each bottle (White and Beckett, 1964). The Ascorbic Acid Method (APHA, AWWA, WPCF, 1990) was then used to determine the phosphorus concentration. A Beckman DU 640 Spectrophotometer was used to determine EPC in mg/L. EPC units were converted to mg P/ kg soil for data evaluation and comparison.

Total kjeldahl nitrogen method

TKN was measured using the Macro-Kjeldahl Method described in Standard Methods for the examination of Water and Wastewater (APHA, AWWA, WPCF, 1990). Both soil and tissue TKN values were determined using the same procedure. Tissue samples were oven dried at 70°C. The soil samples were allowed to air dry at room temperature (20-25°C). A quantity of 0.09 - 0.15 grams of sample was used for both the soil and tissue TKN analysis. A Lab-Line extraction apparatus was used for the distillation process. The resultant solutions from the distillation process were titrated with 0.02 N H_2SO_4 to determine TKN concentration. Specific procedures are well defined in Standard Methods.

Soil elemental analysis

The soil sample elemental analysis was conducted by the VPI&SU Soils Testing and Plant Analysis laboratory. Bioavailable elements were extracted using the Mehlich 3 procedure (Donohue, 1992). The liquid samples were then analyzed on a Jarell-Ash ICAP 9000 ICP to quantify Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, and Zn content.

Tissue elemental analysis

The Nitric Acid-Perchloric Acid Digestion for determination of the elemental composition of plant tissue (APHA, AWWA, WPCF, 1992) was used for the wheat field and pot study tissue samples. The procedure called for one gram of dry plant tissue to be placed in a 50 mL Folin Wu test tube. Concentrated nitric acid (HNO_3; 8mL) was added to the tubes to digest the plant tissue. The mixture was allowed to stand overnight in a fume hood to allow time for complete digestion. A special hood at the VPI Soils laboratory was used for the perchloric digestion procedure due to the explosive potential of the acids. Solids residuals were removed from the solution by centrifuging and decanting the supernatant. The supernatant for each sample was then analyzed by an ICP.

Greenhouse Pot Study

Introduction

A benchscale pot study using PACl sludge to grow lettuce and radish plants was required as part of the AWWARF sludge land application study. The pot study was performed in a VPI&SU horticulture greenhouse with controlled light and temperature. The objective of this study was to monitor the affects of different sludge loading rates (both fresh and aged sludge residuals) on plant growth and also soil and tissue elemental content.

Experimental design

The PACl sludge used in the experiment was collected directly from the settling basins at the Blacksburg-Christiansburg-VPI Water Authority in Montgomery

Co., Virginia. The first sludge samples collected were placed into 5 gallon plastic carboys and were "aged" approximately eight months. The remaining sludge used in the tests was collected from the basins just prior to the start of the greenhouse study. This sludge is referred to as the "fresh" sludge in the study. Both the "aged" and "fresh" sludge had an initial solids concentration of 2-4%. Because of the low dry solids content it was necessary to dewater the sludge to a solids concentration of 20-30% before blending with the soil. Sludge was dewatered by open air drying.

The soil used in the greenhouse pot study was collected from a border strip at the VPI&SU Research Farm sludge application field site. The soil was allowed to air dry and was then hand sieved with a 2 mm wire screen to provide soil size uniformity. This soil was selected due it's good quality for crop growth and the availability of chemical and physical data. This data, presented in Appendix A, had been previously analyzed during the corn growth study (Novak et al., 1993). Forty plastic pots, each containing 2 kg of dried soil, were blended with both "fresh" and "aged" PACl sludge. These treatments will be referred to using the designations listed below:

1. Control - No sludge additions to the soil.
2. 2% aged treatment - Soil was amended with 2% by dry weight of aged PACl sludge.

3. 4% aged treatment - Soil was amended with 4% by dry weight of aged PACl sludge.
4. 8% aged treatment - Soil was amended with 8% by dry weight of aged PACl sludge.
5. Fresh sludge treatment - Fresh PACl sludge was loaded with the same aluminum concentration as the 4% aged treatment (**not by dry solids weight).

The aged sludge was loaded at a 2%, 4%, and 8% sludge to soil ratio based on the total dry solids weight. The total amount of Al added to the soil in the 4% treatment pots was determined to be 3.06 grams Al per pot (2 kg of soil). The 4% fresh sludge pots were loaded with the same aluminum concentration as the 4% aged treatment. The fresh sludge had a higher total Al concentration than the aged sludge, therefore, the new treatment pots required less residual additions in order to match the 4% aged Al concentration. A total of forty pots (four replications for each loading rate and plant type) were then adjusted to a predetermined 30% soil water capacity with distilled water. The pots were seeded with Cherrybelle radishes (<u>Rhaphius sativa</u>) or Black Seeded Simpson lettuce (<u>Lactuca sativa</u>). Lettuce and radish plants were selected due to their short growth periods needed to reach maturity. Pots were arranged in a randomized complete block design on the greenhouse table, and were allowed to grow to maturity (approximately 40 days) with random shuffling of the pots every 10 days. The plants were grown using a controlled 14 hour artificial daylight with night temperatures of 20°C and a day temperature of 30°C. Soil moisture was monitored gravimetrically and maintained near the 30% soil water capacity throughout the experiment.

Data Collection

During the growth period, 48 hour soil water loss in the pots was monitored. The pots were brought up to a predetermined 30% soil water holding capacity with distilled water and allowed to dry in the greenhouse for 48 hrs. The water loss was measured gravimetrically and recorded for each 48 hour period. This process was repeated weekly, a total of 4x, during the course of the growth cycle. When the pot water loss was not being monitored the pots were maintained at the 30% soil water capacity.

The radish and lettuce plants were removed after approximately 40 days of growth. The lettuce and radish wet and dry weights were measured gravimetrically for each residual treatment. The wet weight is the total weight of the plant immediately following harvest. The dry weight is the weight of the plant biomass after all tissue water was removed by oven drying at 70°C for 24 hours. The radish leaves and bulbs were divided and weighed separately. The total wet yield per pot was calculated and divided by the number of plants in each pot to give an average weight per plant. A total of four average weights per plant, one for each residual treatment, were then averaged to get an overall weight per plant for each treatment. Radish leaf, radish bulb and lettuce leaf samples were then oven dried at 70°C for 24 hours and ground into a fine powder for later chemical analysis. The lettuce and radish tissue samples grown in pots with the same sludge treatments were composited together in order to provide a larger amount of sample and to reduce the extensive chemical analysis process. A statistical analysis was not performed on any of the samples that were composited together for chemical analysis.

A small amount of soil was removed from each pot at harvest time and was air dried and sieved to provide a uniform particle size sample. Soil from pots with the same treatments were also composited to provide a larger sample for later chemical analysis and to reduce the amount of samples for analysis. Elemental, EPC, and TKN analysis tests was performed for each composited soil sample. Methods of soil chemical analysis used for wheat field samples were also used for pot study soil and tissue analysis. A statistical analysis was not performed on the composited pot soil samples.

Statistical analysis

A statistical analysis was performed on the corn, wheat, and for *some of the lettuce and radish pot study data. (* only the yield and water loss data were statistically analyzed) The Duncan's Multiple Range test was used to determine the mean separation, the determination of significant differences between residual treatments. The Duncan's test is one of the most widely used multiple range test for agricultural experimentation (Little and Hills, 1978). The 95% confidence interval was used in this study. The Duncan test is a four step procedure.

1.) Calculate the LSD, least significant difference.

2.) Calculate the shortest significant difference (D), to find the position of a given mean in the array of means. (D)=R(LSD) where R is a significance factor for different confidence intervals.

3.) Arrange the means in order of magnitude to test for significant differences. This is done by comparing the largest mean with the smallest and using (D) to find the mean position relative to other treatments. If the differences between means is greater than or equal to (D), then the means are significantly different. Next compare the largest mean with the second smallest and continue this process until a nonsignificant difference is found. These two treatment means are connected and then the process starts over using the second largest mean (Little and Hills, 1978).

The statistical significance is indicated in the tables by the letters a, b, c and d. The means with the same letter were not found to be significantly different at the 0.05 level of confidence. Means with different letters were significantly different. The SAS statistical analysis package on the Virginia Tech computer mainframe was used to simplify the data analysis. The SAS package was programmed to use the Duncan's Multiple Range test (SAS Institute, Cary, N.C.).

Results and Discussion

Wheat Field Crop Growth Study

Soil analysis

Soil samples collected from the field plots at anthesis (the stage prior to wheat head formation and pollination) indicated that an adequate supply of macronutrients and micronutrients necessary for good wheat growth were present. Elemental concentrations were compared with background soil concentrations (Appendix A-1) and also with the control plot elemental concentrations. The initial background soil elemental levels in the field plots were measured prior to residuals application and fertilization. Table 6 shows the analysis of the field soil at wheat anthesis.

The macronutrients analyzed included TKN, K, Mg, Ca, and P. The soil TKN concentrations during the wheat boot stage were 0.10% which was sufficient to support good wheat growth. A second nitrogen addition of 90 kg N/ha was applied to the plots during the early growth period to insure that nitrogen deficiency would not be a problem. The calcium and magnesium concentrations were similar for the sludge treated and control plots. The Ca and Mg concentrations showed no changes compared with the background Ca and Mg soil levels. The potassium concentrations in the treated plots were not found to be significantly different as compared with K in the control plots. The K concentrations for both treated and untreated plots were

Table 6

Soil elemental analysis for wheat field plots prior to wheat growth.

Residual Treatment	Ca	Mg	P	N	K	Mn	Zn	Fe	Al	Cu
			%					ppm		
Control	7.3 ab	2.3 a	0.56 a	0.11 ab	0.54 a	13.8 bc	1.0 c	40.2 a	156.7 c	0.6 b
PACl (x)	8.0 a	1.9 a	0.66 a	0.10 b	0.49 a	16.8 ab	1.8 b	26.5 a	302.1 b	0.6 ab
PACl (2x)	6.5 b	2.2 a	0.54 a	0.12 a	0.41 a	17.3 a	2.2 a	33.0 ab	391.7 b	0.8 a
Alum	8.7 a	2.2 a	0.54 a	0.11 ab	0.54 a	17.8 a	1.1 c	16.7 b	586.9 a	0.6 b

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

below the background (prior to fertilization and sludge addition) soil K concentrations. The Mehlich 3 phosphorus concentrations in the sludge treated plots were not found to be significantly different than the control plots. Mehlich 3 P concentrations as high as 1.5% were measured. Soil P for the field plots prior to wheat growth was 30-40% higher than the background P levels. EPC was reduced in the treated plots by as much as 80% compared to control plot EPC levels.

The soil micronutrients analyzed were Zn, Fe, Al, Mn, and Cu. Soil aluminum concentrations in the treated plots were significantly higher than the control plot concentrations. The increase in Al for the treated plot soil appeared to be the result of elevated Al levels in the alum and PACl sludges applied. Aluminum levels in the soil prior to wheat growth were found to be at lower concentrations than the background Al levels. Looking back at the history of the plot soil elemental levels (see Appendix A) measured during the corn study, there was a large increase in soil Al in the sludge treated plots as a result of sludge additions; however, a year and a half after sludge applications the Al concentrations were found to be at background levels. This was thought to be due to mixing of the top six inches of soil with the lower soil layers by mechanical tilling, as well as, losses from soil leaching. Other elements analyzed showed a similar pattern of soil elemental concentrations as did the soil Al levels. The copper, iron, zinc and manganese concentrations in the sludge treated plots appeared to increase with initial residual additions; however, these elemental concentrations prior to wheat growth were also equal or less than their respective background levels.

Tissue analysis

A complete elemental analysis for the wheat leaf tissue samples collected prior to anthesis is shown in Table 7. The analysis showed that sufficient concentrations of macro- and micronutrients in the leaf tissue were present to support good growth (Donohue et al., 1987). The only tissue elemental concentrations that showed a significant difference, when compared to the control plot tissue concentrations, were phosphorus and zinc. Other elements analyzed showed no significant differences in concentrations between the treated and control plots.

Tissue P was found to be significantly higher for the wheat grown in the control plots as compared with wheat leaves from sludge treated plots. The control plot and the alum sludge treated plots all had similar P concentrations of approximately 0.25-0.30%. These P concentrations were adequate for good wheat growth (Donohue et al., 1987). The wheat leaf tissue analysis showed TKN concentrations of 3.4-3.6% for both the treated and control plots. Leaf tissue TKN from the alum and PACl treatments were comparable to the control plot TKN concentrations. The tissue Zn concentrations appeared to increase with alum and PACl treatments. A 70% increase in Zn concentration as compared with the control

Table 7

Tissue elemental analysis for wheat leaves collected prior to anthesis.

Residual Treatment	Ca	Mg	P	N	K	Mn	Zn	Fe	Al	Cu
			%					ppm		
Control	0.5 a	0.2 a	0.3 a	3.5 a	1.1 a	97 a	1.1 b	112 a	3.9 a	<0.1
PACl (x)	0.5 a	0.2 a	0.3 a	3.4 a	1.1 a	83 a	2.9 a	105 a	4.1 a	<0.1
PACl (2x)	0.5 a	0.2 a	0.3 a	3.6 a	1.3 a	103 a	2.6 a	112 a	4.9 a	<0.1
Alum	0.4 a	0.2 a	0.3 a	3.5 a	1.1 a	91 a	3.7 a	113 a	4.8 a	<0.1

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

was measured in the alum treated plots. The increases in tissue Zn concentrations were directly related to the elevated Zn concentrations present in the alum and PACl sludge (see Table 1 for sludge elemental levels). However, the highest Zn concentration (almost 4 mg/kg) found in the wheat leaf tissue is considered to be below normal plant tissue Zn concentrations of 10-100 mg/kg (Elinder and Piscator, 1977).

Grain yield

At harvest, the grain yield analysis showed no significant differences between the sludge treated and control plots. Table 8 shows the grain yield statistical analysis. The average wheat grain yields for the field plots was almost 7000 kg/ha. The plot yield averages were found to be higher than the Virginia state average for wheat grain (Donohue et al., 1987). The grain production data demonstrated that alum and PACl sludge additions did not negatively impact wheat growth and grain yield.

Biomass yield

Total wheat biomass at harvest was also measured. Average biomass yields are presented in Table 9. The total wheat biomass is a measure of the total weight of whole wheat plants (stems, leaves, and seeds) for a given sectional area of each plot. The biomass yield for each field plot was calculated and then converted to

Table 8

Summary of the yield parameters for soft red winter wheat grown in soil treated with water treatment residuals (WTR).

Loading	% Moisture	Test weight (lb/bu)	Yield (kg/plot)	Yield (kg/ha)	Yield** (bu/acre)
Control	14.2 a	55.9	10.3 a	6,400 a	103
PACl (1x)	14.6 a	55.5	11.0 a	7,200 a	115
PACl (2x)	14.4 a	55.8	11.6 a	6,800 a	110
Alum	14.5 a	55.8	11.3 a	7,000 a	112

**Individual plot wheat yields

Plot No.	Control (bu/acre)	PACl (1x) (bu/acre)	PACl (2x) (bu/acre)	Alum (bu/acre)
1	98	115	99	117
2	71	116	111	118
3	118	118	114	105
4	125	109	114	109
Mean	103	115	110	112
Standard Deviation	23.9	3.7	7.3	6.5

Table 9

Summary of the wheat biomass yield and the individual wheat components grown in soil with WTR additions.

Loading	Seed weight (g)	Stem weight (g)	Head weight (g)	Biomass (kg/ha)
Control	1.41 a	0.30 a	1.69 b	11,600 a
PACl (1x)	1.41 a	0.28 a	1.67 b	11,700 a
PACl (2x)	1.48 a	0.30 a	1.75 ab	12,200 a
Alum	1.56 a	0.25 a	1.90 a	13,000 a

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance.

units of kg total biomass/ha. Biomass yields in sludge treated plots were not found to be significantly different than the control plots.

Yield analysis

Whole wheat plants were randomly collected throughout each of the twenty field plots, oven dried, and then separated into grain, stem, and head components. The total weight was then measured for each component. A statistical analysis comparing the different component weights showed that the head weights were significantly different lower than the control head weights. Table 9 shows the analysis of the wheat component yields for each treatment. The other wheat components analyzed showed no significant differences between the treated and control plots.

Wheat grain - elemental analysis

A statistical analysis performed on the grain tissue data showed that all elements analyzed, with the exception of the iron, had no statistical differences between sludge treated and control plots. (See Table 10 for the elemental analysis results) The wheat grain Fe concentration was lower in the treated plots as compared with the grain tissue Fe from the control plots. Aluminum and copper concentrations were both below detectable levels. The untreated grain tissue phosphorus concentrations were not statistically different than the grain tissue P grown in sludge

Table 10

Summary of elemental analysis for wheat grain grown in soil with WTR additions.

Residual Treatment	Mn	Al	Zn	Cu	Fe	K	Mg	Ca	N	P
	ppm					%				
Control	41.8 a	<1.0	10.2 a	<0.1	35.8 a	0.4 a	0.1 a	0.03 a	1.6 a	0.4 a
PACl (x)	39.6 a	<1.0	17.5 a	<0.1	29.2 a	0.3 a	0.1 a	0.03 a	1.5 a	0.4 a
PACl (2x)	40.9 a	<1.0	9.3 a	<0.1	26.1 b	0.4 a	0.1 a	0.03 a	1.4 a	0.3 a
Alum	41.2 a	<1.0	9.2 a	<0.1	28.8 a	0.4 a	0.1 a	0.03 a	1.4 a	0.3 a

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

treated soil. Total kjeldahl nitrogen concentrations in the treated plots also showed no significant differences as compared with the control TKN concentrations.

Soil analysis - after wheat harvest

A complete soil elemental analysis was performed after the wheat harvest. Results of the analysis are listed in Table 11. Soil samples from each plot were collected after the soil was mechanically rotavated and prepared for tall fescue planting. A statistical analysis of the macronutrients in the soil showed that only the potassium levels were significantly different between sludge treated and control plots. Soil K levels were found to be higher as compared with the control K concentrations in the alum treated plots, and were found to be similar in the PACl treatments. A comparison of the post wheat field macronutrient concentrations and the background soil macronutrient concentrations (found in Appendix A) revealed no changes in elemental Ca and Mg levels. The K concentration was found to be below background levels.

The data in Figure 1 shows the soil P concentrations for the field plots over the two year study period. The Mehlich 3 P concentration revealed that, after two years and two crop rotations, the field soil was again at the same levels as the background soil P concentrations prior to fertilizer application. Background soil EPC levels for the field plots are presented in Appendix A. EPC values measured during the wheat field study are shown in Table 12. EPC concentrations for sludge treated

Table 11

Summary of the soil elemental analysis for the wheat field plots after wheat harvest.

Residual Treatment	Ca	Mg	P	K	Mn	Zn	Fe	Al	Cu
	%				ppm				
Control	6.1 a	1.9 a	0.4 a	0.6 b	12.8 b	1.0 c	40.3 a	147.0 c	1.2 a
PACl (x)	5.3 a	1.5 a	0.4 a	0.7 ab	14.3 ab	1.4 b	23.4 ab	220.0 cb	1.2 a
PACl (2x)	7.1 a	1.9 a	0.3 a	0.6 b	16.5 ab	1.7 a	31.9 ab	268.0 b	1.3 a
Alum	7.0 a	2.0 a	0.4 a	0.8 a	17.7 a	1.1 c	16.3 b	477.0 a	1.1 a

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

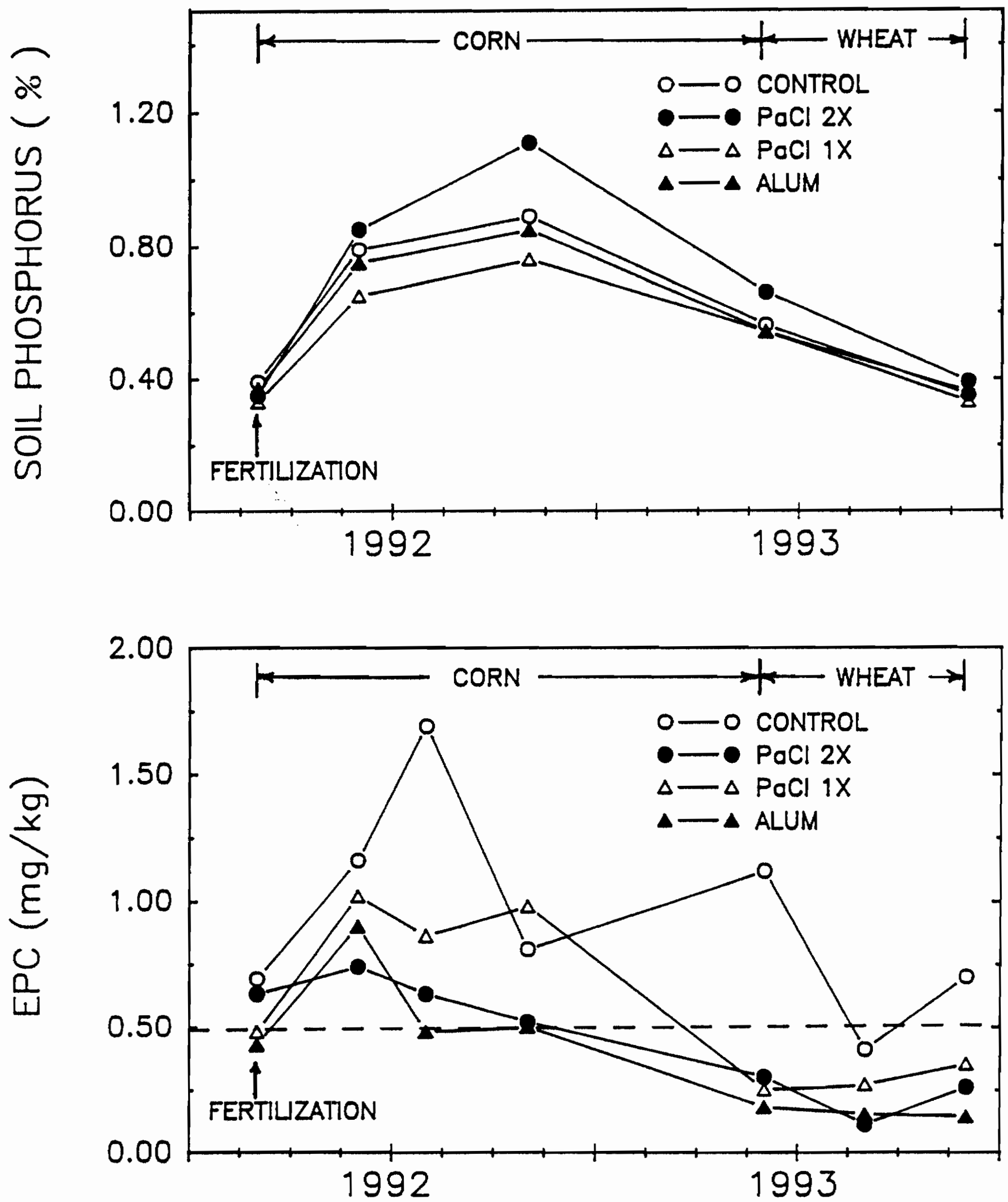

Figure 1 History of soil Mehlich 3 phosphorus and equilibrium phosphorus concentrations throughout the two year water treatment sludge land application study.

Table 12

Summary of the statistical analysis for the wheat field equilibrium phosphorus concentration data.

Residual Treatment	Spring 1993 EPC (mg/kg)	Summer 1993 EPC (mg/kg)	Fall 1993 EPC (mg/kg)
Control	0.11 a	0.41 a	0.70 a
PACl (x)	0.25 b	0.27 ab	0.35 b
PACl (2x)	0.30 b	0.11 b	0.26 bc
Alum	0.18 b	0.15 b	0.14 c

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

plots throughout the wheat growth study were below 0.5 mg P/kg soil. The control soil EPC was found to be 0.1 mg/kg at the beginning of wheat growth and was found to be 0.7 mg P/kg soil at wheat harvest. Increases in EPC could be due to P mineralization aided by increased spring and summer rainfall. Figure 1 shows the EPC concentrations over the two year study period. Although the soil EPC levels during the wheat growth study were much lower than EPC during the corn study no plant P deficiency or loss of yield was noted.

The soil micronutrient analysis at wheat harvest showed no changes in Zn, Fe, and Mn concentrations as compared with the wheat boot stage soil elemental analysis (Table 11). The soil Al concentration for each plot treatment continued to decline over time. The sludge treated plots remained higher in Al concentration than the control plots. The Al in the soil after the wheat harvest was found to be below the background levels, with the exception of the alum treated plots. The elemental Cu concentration appeared to increase to levels closer to the original background Cu concentrations. Post wheat field elemental Cu levels were not significantly different from the control.

Summary

Soil macro- and micronutrients in both the sludge treated and control plots were found to be at adequate levels to support good wheat growth (Donohue et al., 1987). Water treatment sludge additions caused an increase in most of the soil elements analyzed as compared with the background soil levels; however, most of the increases were found to be insignificant.

The tissue elemental analysis for wheat leaves collected prior to anthesis showed no significant differences between the wheat grown on sludge treated plots versus the control plots. All tissue elemental concentrations prior to anthesis were found to be at normal wheat leaf tissue levels (Donohue et al., 1987). The statistical analysis for the grain tissue elemental data showed no significant differences in concentration.

The grain yield showed no significant differences between the sludge treated and control plots. Total biomass yields for the treated plots were not found to be significantly different from the control plots.

Soil P levels (obtained using the Mehlich 3 method) in the field plots prior to wheat growth, were found to be adequate to support good wheat growth. Soil EPC levels in the treated plots were found to be below EPC levels increased during the corn growth study; however, wheat yields were not negatively impacted by this reduction in EPC.

Lettuce pot study results

Yield

The lettuce wet weight per plant for the control, 2%, and 4% aged sludge treatments demonstrated no statistical differences at the 95% confidence level.

Table 13 shows the results of the statistical analysis for the lettuce yield. The wet yield for the fresh (sludge directly from settling basin) sludge treatment was found to be significantly less than the yields for the three aged residual treatments and the control lettuce yields.

The lettuce dry leaf yield per plant had a similar statistical trend as the wet yield weights with the exception of the 8% aged sludge treatment. The control, 2%, and 4% treatments showed no significant difference in dry yield. The 8% treatment dry yield was found to be significantly less than the control, 2% aged, and 4% aged sludge treatments. The fresh sludge treatment produced the lowest overall dry leaf yield. Lettuce harvest and chemical analysis data for individual pots are presented in Appendix C.

Water loss

Water loss by plant uptake and surface evaporation was monitored for each pot. An analysis of the lettuce pot soil for the average 48 hour water loss, presented in Table 13, showed no significant differences in loss between the different sludge loading rates. Table 14 shows the results for each of the 48 hour water loss monitoring periods for each residual treatment which are presented in Appendix B. Water loss rates are shown in the table to change, considerably, from one trial to the next. These changes are due to the varying weather conditions during the sampling periods which had an affect

Table 13

Summary of the statistical analysis of the lettuce pot study 48 hour water loss and yields.

Soil Treatment	48 hour water loss	Fresh leaf weight	Dry leaf weight
Control	236 a	5.45 a	0.54 a
2% Old	215 a	5.71 a	0.46 a
4% Old	223 a	5.74 a	0.49 a
8% Old	205 a	5.00 a	0.36 b
4% New	206 a	3.53 b	0.27 c

*-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

Note: Water loss is reported as g/pot, weights are in g/plant.

Table 14

Data from the 48-hour water loss trial periods measured from the lettuce pots.

Sludge Loading	48-Hour Water Loss Monitoring			
	Trial Period 1	Trial Period 2	Trial Period 3	Trial Period 4
Control	100	250	360	210
2% Aged	75	180	330	260
4% Aged	90	200	320	285
8% Aged	80	190	330	225
4% Fresh	100	195	320	210

*Water loss is reported in ml/pot.

on Greenhouse temperatures. Overall, sludge additions to the lettuce pots did not change the soil moisture retention capacity.

Equilibrium phosphorus concentration

The equilibrium phosphorus concentration has been proposed to be a measure of the labile or plant available phosphorus in the soil solution. Lettuce pot soil EPC values are listed in Table 15. The lettuce pot soil EPC was found to sharply decline with increased sludge additions. A maximum EPC level was measured in the control pot soil. The 2%, 4%, and 8% aged treatments had a 55%, 70% and 95% decrease, respectively, in soil EPC as compared with the control. The fresh sludge treatment EPC was 80% less than the 4% aged treatment EPC and 90% less than the control EPC.

Figure 2 shows the dry lettuce yield as a function of soil EPC. The figure suggests that increased EPC concentrations in the lettuce pot soil resulted in a higher dry weight yield per plant. The figure shows that the fresh sludge and 8% aged sludge treatments had soil EPC values below 0.5 mg P/kg soil. Dry weight yield in soil with EPC levels below 0.5 mg P/kg soil was demonstrated to significantly decrease lettuce plant growth. This decrease in lettuce yield is evident in the figure.

Figure 3 shows that the lettuce tissue P concentrations were not affected by residuals additions. Sludge additions to the soil appeared to decrease the soil EPC,

Table 15

Summary of elemental analysis for the composited lettuce pot soil.

Residual Treatment	Ca	Mg	P	N	K	Mn	Zn	Fe	Al	Cu	B	EPC (mg/kg)
	%					ppm						
Control	7.9	2.5	0.7	0.2	0.3	20.1	3.4	33.4	177	0.4	0.4	1.5
4% New	8.4	2.7	0.7	0.2	0.3	29.4	4.5	33.2	450	0.7	0.4	0.2
2% Old	7.9	2.4	0.7	0.1	0.2	24.0	2.2	33.0	260	0.5	0.3	0.5
4% Old	7.8	2.4	0.7	0.1	0.3	23.7	2.7	30.4	275	0.1	0.3	0.7
8% Old	8.6	2.7	0.7	0.2	0.3	33.1	3.6	31.2	590	0.8	0.3	0.1

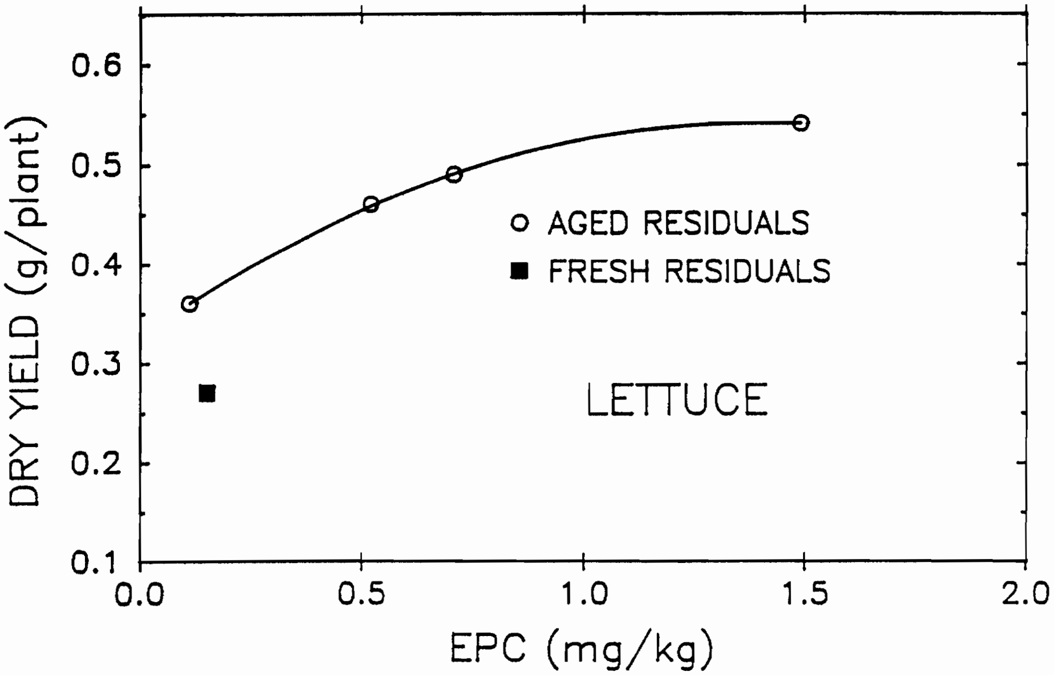

Figure 2 Lettuce pot soil equilibrium phosphorus concentration as a function of lettuce leaf dry weight per plant.

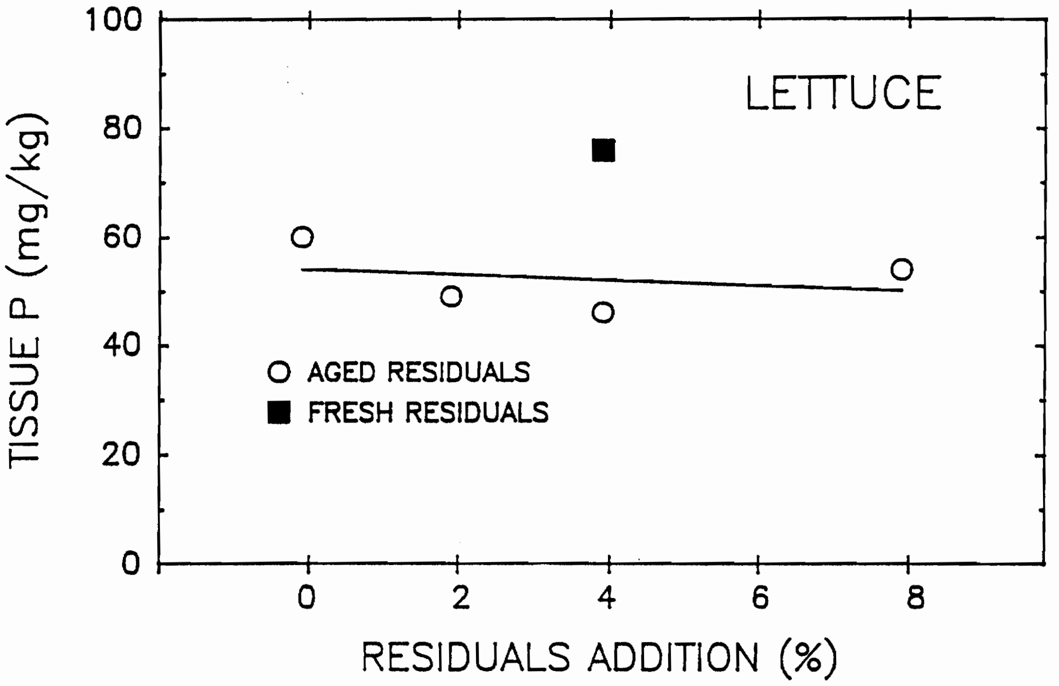

Figure 3 Lettuce tissue phosphorus as a function of WTR sludge addition.

however, the reduced soil EPC levels had no effect on the lettuce tissue P concentrations.

Total Kjeldahl Nitrogen

Sludge additions to the lettuce pots did not change the composited soil TKN concentrations as compared with the control soil TKN levels. TKN values are listed in Table 15.

Composited lettuce tissue TKN concentrations are presented in Table 16. The TKN concentrations were slightly lower in the control lettuce pots as compared with the pots that received sludge additions. Concentrations of 1.5-2.5% measured from the lettuce tissue samples were considered to be at sufficient levels to be non-limiting for growth (Donohue et al., 1987).

Soil Elemental Analysis

A composited lettuce pot soil elemental analysis presented in Table 15 reported soil concentrations for Ca, Mg, Mn, P, K, Zn, Fe, Al, Cu and B. The only elemental concentrations that displayed an increase in concentration with higher sludge loading rates were aluminum and copper. The soil collected from the 8% aged sludge treatment had a 70% higher Al concentration than the control pot soil. The 2% and 4% aged treatments displayed a 30% increase in soil Al concentration over the control. The fresh sludge treatment had almost a 40% higher Al

Table 16

Summary of elemental analysis for the composited lettuce leaf tissue.

Residual Treatment	S	Mn	Al	Zn	Cu	Fe	K	Mg	Ca	N	P
	ppm						%				
Lettuce leaf control	34	52	84	27	0.2	613	1.9	1.1	1.5	1.5	0.6
4% New	50	75	104	61	0.2	760	5.0	1.2	2.3	2.0	0.8
2% Old	40	80	63	35	0.2	420	3.1	1.7	1.8	2.2	0.5
4% Old	36	102	150	37	0.2	870	3.0	1.6	1.8	1.8	0.5
8% Old	45	130	140	64	0.2	830	4.2	1.9	2.3	2.5	0.5

concentration than the 4% aged treatment. Figure 4 shows that the increased soil Al concentrations did not appear to affect the uptake of P into the lettuce tissue. The Cu concentration in the 8% aged treatment was found to be 40% higher than the control concentration. The fresh sludge treatment was found to contain a 20% higher Cu concentration as compared with the 4% aged sludge treatment. The remaining elements analyzed showed no increase or decrease in concentration as compared with the control.

Tissue Elemental Analysis

Composited lettuce leaf tissue samples were analyzed to determine the concentrations of ten different elements: K, Mg, Mn, S, P, Al, Zn, Ca, Cu, and Fe. Table 16 shows the results of the lettuce tissue analysis.

Lettuce tissue phosphorus concentrations did not appear to change appreciably with aged residual additions as compared with the control pot soil P. Figure 5 shows the tissue elemental concentrations of manganese, and zinc at the different sludge loading rates. Mn concentrations in lettuce tissue are shown to increase as much as 60% with sludge additions. This increase was almost linearly related to the percent loading of aged sludge added to the pot soil. Elemental Zn concentrations in lettuce tissue also increased with sludge additions. The regression analysis for both elements revealed r-squared values greater than 95%.

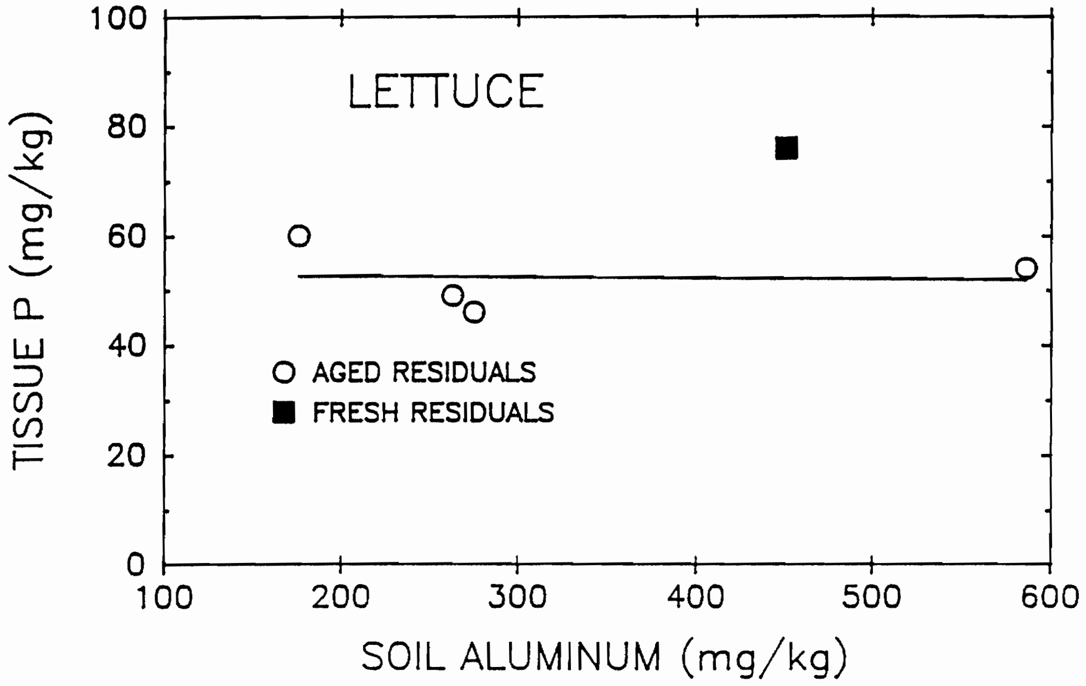

Figure 4 Lettuce tissue P as a function of the Mehlich 3 aluminum concentrations in the lettuce pot soil.

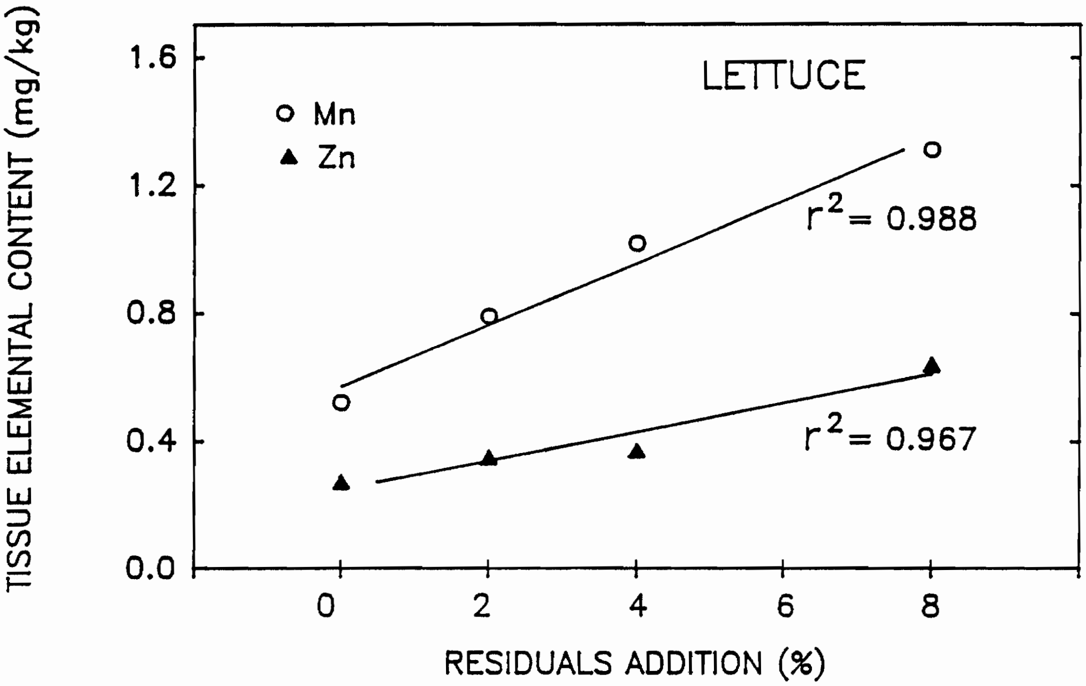

Figure 5 Lettuce tissue manganese, aluminum and zinc concentrations as a function of WTR residuals addition.

Other elements that displayed an increase with sludge additions were potassium, magnesium and calcium. Of these elements, the tissue K showed the largest increase as compared with the control tissue.

Summary

The lettuce dry matter yield was shown to decrease with increased sludge additions. No significant differences in dry matter yield were found between the control and the 2% and 4% aged sludge treatments. However, the 8% aged and fresh sludge treatments produced significantly lower yields as compared with the control.

The sludge treatments showed no significant differences in 48 hour water loss as compared with the control pots. Water loss in soil is typically a function of the number of plants growing in the pot and the total plant biomass per pot. Larger plants would require more water to support growth and thus would have increased levels of water loss. Looking at water loss from a nutrient supply standpoint, reduced growth would lead to smaller plants and thereby reduce water loss.

The EPC levels predicted a potential Mehlich 3 P deficiency in the pots. The fresh sludge and 8% aged treatments had the lowest EPC levels < 0.5 mg P/kg soil. This appeared to result in a decreased lettuce yield. The pots with the higher EPC levels produced the greatest lettuce yields. The fresh sludge addition was shown to cause a greater reduction in EPC as compared with the aged sludge. Other soil elements analyzed did not change with increased sludge additions, with the exception of Mehlich 3 Al and Cu. Both were expected to increase due to elevated levels present in the PACl sludge additions. Elevated soil Al levels did not appear to affect phosphorus uptake into the lettuce plants.

Lettuce tissue manganese, aluminum, zinc, potassium, magnesium, and calcium concentrations were found to be higher in the sludge treated pots as compared with the control tissue concentrations. There appeared to be a direct relationship between increased sludge loading rates and tissue concentrations of Mn, Zn, and. All three elements increased with sludge additions. Tissue concentrations of Mn, Al, Zn, K, Mg, and Ca in the sludge treated pots at lettuce harvest were found to be at concentrations typical of similarly related crops (spinach, etc.) produced for human consumption (Donohue et al., 1987).

Radish Pot Study Results

Yield

The yield data and statistical analysis from the radish pot study are presented in Table 17. Radish fresh and dry yield data showed that the 8% treatment produced the highest wet leaf yield of 4.68 g/leaf. A statistical analysis determined that the 8% aged treatment leaf yield was significantly higher than the control, 2%, and 4% aged treatments. The fresh sludge treatment wet leaf yield was found to be lower,

Table 17

Summary of the statistical analysis of the lettuce pot study 48 hour water loss and yields

Soil Treatment	48 hr. Water Loss	Fresh Leaf Weight	Fresh Root Weight	Dry Leaf Weight	Dry Root Weight
Control	184 b	2.23 bc	4.81 b	0.32 b	0.39 b
2% Old	198 b	2.46 b	3.16 b	0.36 b	0.33 bc
4% Old	208 b	2.90 b	4.39 b	0.38 ab	0.40 b
8% Old	238 a	4.68 a	7.40 a	0.46 a	0.60 a
4% New	145 c	1.50 c	2.72 b	0.17 c	0.22 c

* - Values within columns followed by the same letter are not statistically different at 0.05 level according to Duncan's Multiple Range test

Note: Water loss is reported as g/pot, weights are in g/plant.

although not significantly lower, than the control wet leaf yield. The radish leaf wet yield was found to increase with higher sludge additions.

The radish root data showed that the 8% aged sludge treatment also produced the highest wet root weight of 7.4 g/root. The 8% yield was found to be significantly higher than any of the other treatments. The control, 2%, 4% aged and fresh sludge treatments all demonstrated no significant differences in wet root yield. The 8% aged sludge treatment wet root yield was 35% higher than the control yield, which was the second highest. The radish dry leaf yield analysis (Table 17) demonstrated no significant differences between the 2%, 4%, and 8% aged treatments. These treatments produced the overall highest dry leaf yields. The 2% and 4% aged dry leaf yields were not significantly higher than the control. The highest average dry leaf yield was 0.46 g/leaf produced in the 8% aged treatments. The lowest production of 0.17 g/leaf was found in the fresh sludge treated pots.

The 8% aged treatment had the highest dry root yield at 0.6 g/root. This yield was significantly higher than the control and other fresh and aged sludge treatments. The radish dry root yield showed no significant differences between the control, 2% and 4% treatments. The fresh sludge treatment had a significantly lower yield of 0.22 g/root than the 4% aged treatment and the control. See Appendix C for individual pot data.

Water loss

A statistical analysis of the average 48 hour water loss data is presented in Table 17. The water loss data measured from the radish pot soil showed a significantly higher average loss for the 8% treatment as compared with the other treatments. Table 18 shows the results of the 48 hour water loss monitoring periods for each sludge treatment. The control, 2% and 4% aged treatments had the second highest 48 hour water losses. No apparent differences in water loss were found between these treatments. The fresh sludge treatment had the lowest water loss which was 30% less than the 4% aged treatment. The 48 hour water loss for the radish pots was shown to increase with higher residual loading rates.

The fresh and dry radish yields increased in the pots with higher rates of soil water loss. The 8% treatment had the highest 48 hour water loss and also the highest radish leaf and root yield. The fresh sludge treatment had the overall lowest average water loss and the lowest yields.

Equilibrium phosphorus concentration

The EPC values for the radish pot soils are listed in Table 18. Soil EPC for the radish pots appeared to decrease when WTP sludge was added. A maximum EPC value of 1.4 mg/kg was measured in the control soil. The 2%, 4%, and 8% aged treatments showed a 70-75% decrease in soil EPC as compared with the control. The fresh sludge treatment had an EPC 70% less than the 4% aged

Table 18

Data from the 48-hour water loss trial periods measured from the radish pots.

	48-Hour Water Loss Monitoring			
Sludge Loading	Trial Period 1	Trial Period 2	Trial Period 3	Trial Period 4
Control	110	170	290	175
2% Aged	130	190	290	195
4% Aged	120	200	320	190
8% Aged	140	250	350	225
4% Fresh	90	150	220	150

*Water loss is reported in ml/pot.

treatment and 90% less than the control. Figure 6 shows the radish leaf and root dry yields as a function of the radish pot soil EPC. Both the lowest yield and the lowest EPC occurred as a result of the addition of fresh sludge.

Increased EPC in soil did not produce an increase in the radish leaf or root tissue P concentrations. Figure 7 shows the radish root and leaf tissue P concentration as a function of EPC levels in the pot soil. The fresh sludge treatments had the lowest EPC, but had mid to high levels of tissue P.

Total kjeldahl nitrogen

The soil TKN for the radish pots did not show an increase or decrease in concentration with higher sludge treatments. The soil TKN ranged from 0.12-0.15%.

The TKN concentrations for both the radish leaf and root tissue also did not change with higher sludge treatments. The leaf TKN concentrations ranged from 2-3%, while the root tissue TKN values averaged 1.5%. Soil TKN values are listed in Table 18, tissue TKN values are presented in Table 19.

Soil elemental analysis

The soil elemental analysis for the radish pots determined concentrations for Ca, Mg, Mn, P, K, Zn, Fe, Al, Cu, and B. (see Table 18) Although some of the elemental concentrations appeared to increase with higher sludge loading rates, the largest increase was the Al concentration. The 8% aged treatment had an Al

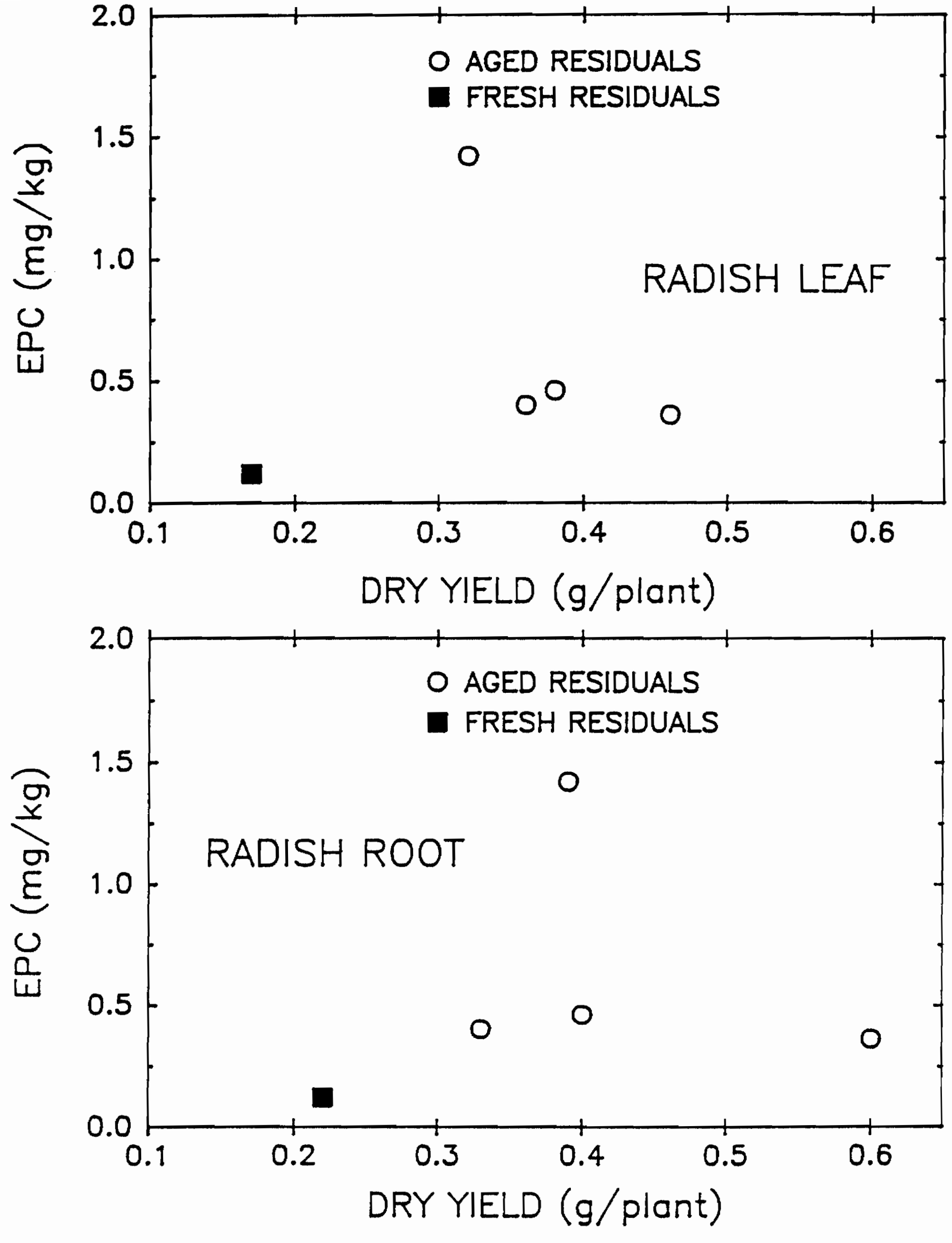

Figure 6 Radish pot soil equilibrium phosphorus concentration as a function of radish dry leaf and root weights per plant.

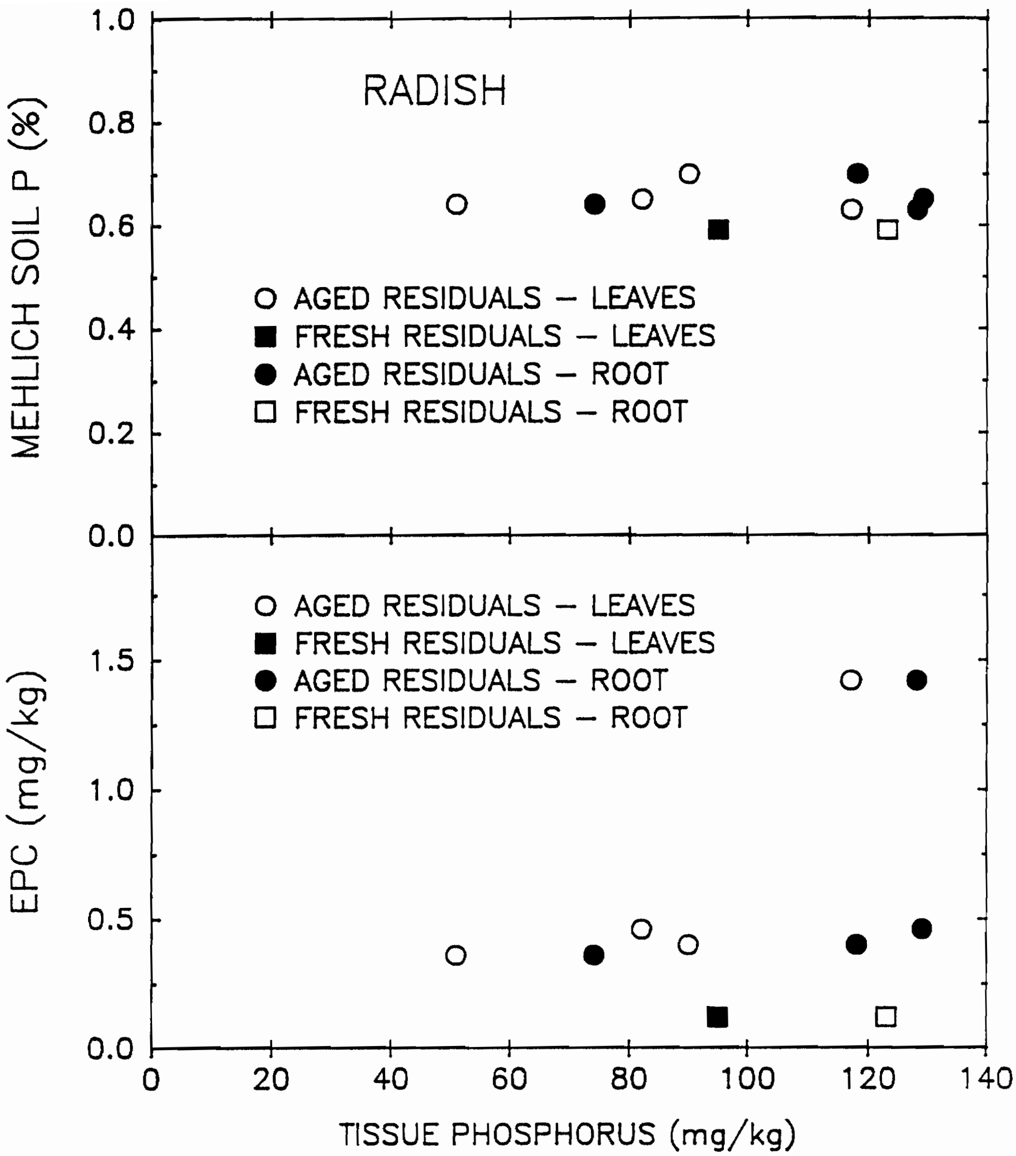

Figure 7 Radish leaf and root tissue phosphorus as function of soil EPC and Mehlich 3 phosphorus concentrations.

Table 19

Summary of elemental analysis for the radish pot soil

Residual Treatment	Ca	Mg	P	N	K	Mn	Zn	Fe	Al	Cu	B	EPC (mg/kg)
	%					ppm						
Control	7.80	2.5	0.63	0.15	0.26	22	3.60	34	200	0.48	0.29	1.42
4% New	8.40	2.6	0.70	0.15	0.53	30	4.27	36	480	0.61	0.34	0.12
2% Old	8.06	2.5	0.65	0.13	0.22	20	2.83	32	304	0.54	0.30	0.40
4% Old	8.17	2.6	0.64	0.13	0.19	21	2.90	31	290	0.52	0.29	0.46
8% Old	7.94	2.5	0.59	0.11	0.19	28	3.12	30	450	0.67	0.30	0.36

concentration 55% higher than the control soil and the fresh sludge treatment had the highest average soil Al concentration.

Tissue Elemental Analysis

Both the radish leaf and root tissue samples were analyzed to determine the concentration of 10 different elements. These elements were K, Mg, Mn, S, P, Al, Zn, Ca, Cu, and Fe (see Table 20).

Radish leaf and root tissue phosphorus concentrations were lowest for the soil which received the 8% aged sludge additions. The content in the radish leaf tissue appeared to decrease with sludge addition; however, radish roots were generally not impacted.

Figure 8 shows the radish leaf tissue aluminum content as a function of residual additions. The Al in the leaf tissue was shown to increase linearly with sludge additions. The Al in the radish leaf tissue increased 60% from the control to the 8% aged sludge treatment. The Zn concentrations for the leaf and root tissue appeared to decrease with higher aged residual loading rates. (Table 15) Elevated Zn concentrations in the sludge might be expected to cause an increase tissue Zn, but this was not observed for the aged sludge treatments. The Zn levels for the fresh sludge additions appeared to be higher than the control Zn tissue levels.

Table 20

Summary of elemental analysis for the radish leaf and root tissue.

Residual Treatment	S	Mn	Al	Zn	Cu	Fe	K	Mg	Ca	N	P
	ppm						%				
Radish leaf control	81	61	28	64	0.2	322	3.0	2.1	4.9	2.7	1.2
4% New	195	94	56	67	0.2	602	1.5	2.2	5.4	2.8	1.0
2% Old	140	61	37	62	0.2	322	3.1	2.1	4.8	2.6	0.9
4% Old	150	72	50	58	0.2	450	2.3	2.3	4.9	2.4	0.8
8% Old	155	82	67	42	0.2	532	2.2	2.7	6.2	2.4	0.5
Radish root control	74	21	87	48	0.2	453	3.3	0.4	0.8	1.4	1.3
4% New	140	40	134	51	2.1	1,900	3.0	0.5	0.8	1.5	1.2
2% Old	146	24	99	37	0.2	517	3.9	0.5	0.8	1.5	1.2
4% Old	140	23	124	386	0.2	671	4.1	0.5	0.8	1.6	1.3
8% Old	115	20	70	29	0.2	410	3.5	0.4	0.7	1.4	0.7

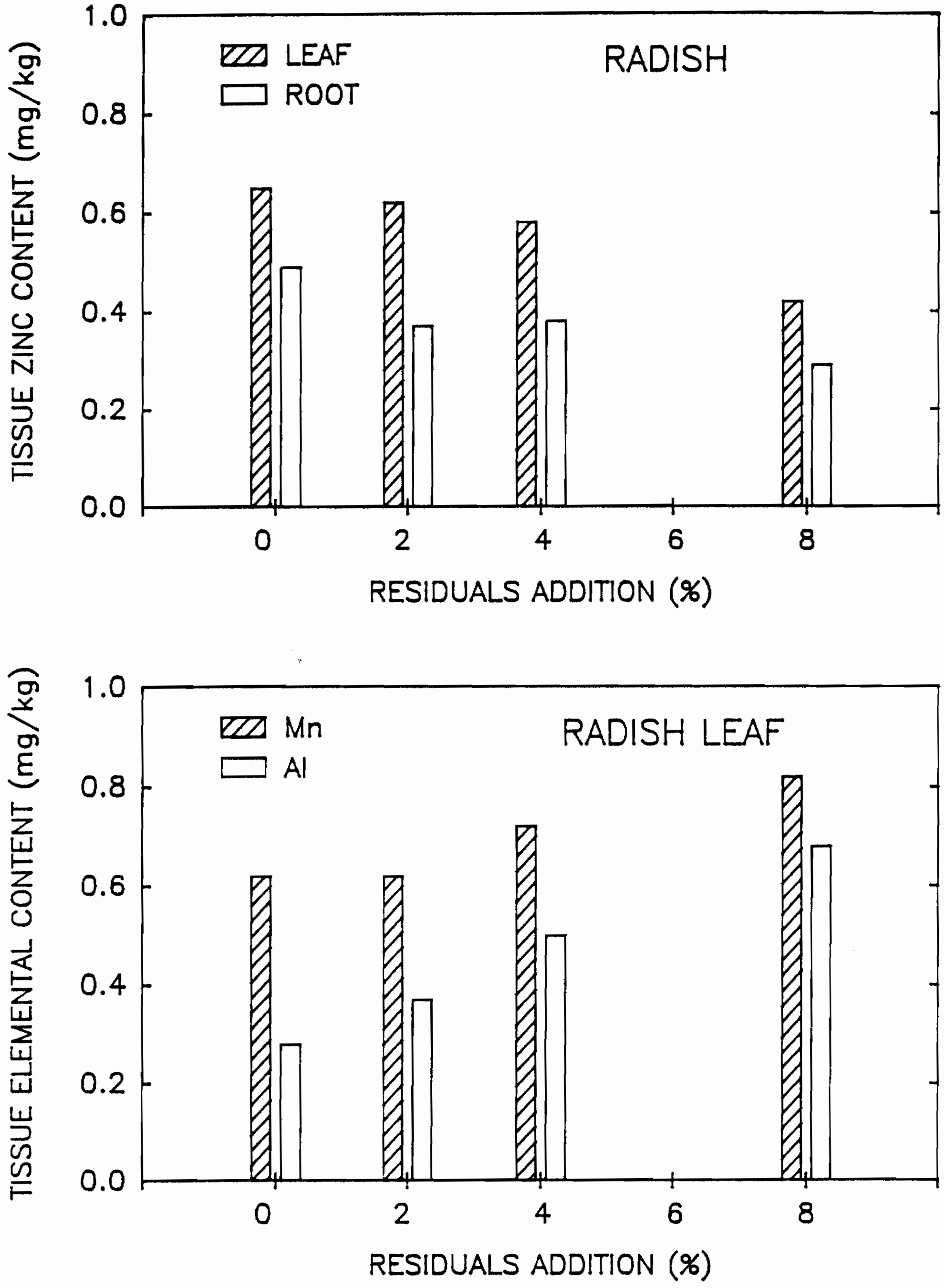

Figure 8 Radish leaf and root tissue zinc concentration and radish leaf tissue manganese and aluminum concentrations as a function of WTR residuals addition.

Summary

The addition of aged water treatment sludge did not cause a decrease in dry radish leaf and root yields. In contrast, fresh sludge additions decreased both leaf and root dry matter yields.

Water loss increased with aged sludge additions and decreased with the addition of fresh sludge. Water loss was most likely a function of the number of plants growing in the pot and the total plant biomass per pot. Larger plants would require more water to support growth and thus would increases pot water loss.

Similar to the lettuce pot study, a potential P deficiency was also predicted by low soil EPC levels. EPC concentrations were found to be sufficient for good plant growth in all of the treatments except the 4% fresh sludge treatment. The decreased EPC resulted in a significant reduction in radish leaf and root yield.

Addition of sludge increased soil aluminum levels. The remaining elements did not appear to change substantially as compared with the control.

The tissue elemental analysis showed that phosphorus concentrations were reduced in the tissue of radish plants grown in sludge treated pots. Manganese and aluminum increased with sludge additions, while zinc concentrations decreased with sludge additions. Radish plant tissue concentrations of Mn, Al, K, Mg, and Ca after radish growth in all of the sludge treated pots were well below levels which might preclude human consumption (Donohue et al., 1987).

Summary and Conclusions

The alum sludge land application field and bench scale studies focused on a number of parameters that were critical for the determination of crop growth. The parameters investigated in the study were crop growth and yield, soil moisture retention, soil elemental accumulation and nutrient supply, tissue metals accumulation and nutrient uptake. The soil EPC phosphorus levels and their resultant effects on crop yields were also studied. Crop yield data was the most important parameter used for determining the viability of land applying alum sludge as an alternative method of disposal. The other parameters mentioned significantly influence crop yield and were, therefore, monitored in order to better understand the reasons for variations in crop yield.

The primary conclusion of the research is that aged PACl and alum additions to soil, with proper conventional soil management practices, should have no negative impacts on crop yield. The following observations summarize the research findings:

Wheat field conclusions

- Sludge additions had no negative effects on wheat grain or biomass yields. The grain yield for the treated plots exceeded the Virginia state average (Donohue et al., 1987).

- Short term metals accumulation in the soil was not found to be a problem. Sludge treated and untreated soils had similar elemental concentrations.
- Soil aluminum levels were significantly increased, however, after two crop rotations utilizing conventional agricultural practices, the soil Al concentrations were found to be similar to background Al levels.
- Wheat leaf tissue slightly increased in Al concentration as compared with the control. This increase in Al concentration was not found to be significant. Other tissue elemental concentrations were at or below normal levels.
- The EPC test was not a good predictive tool for determining P deficiency in wheat field soil. Reduced EPC levels had no affect on wheat growth or yield.
- Anticipated phosphorus binding, associated with sludge additions to soil, did not pose a problem during the growth cycle of the second crop of a typical three crop rotation.

Lettuce pot study conclusions

- Fresh and aged sludge additions decreased lettuce yields. The 8% aged and fresh sludge treatment yields were significantly less than the control.
- Soil elemental concentrations were similar to the control, except for the aluminum and copper levels. Al and Cu had increased concentrations.

- Lettuce tissue elemental concentrations of several micro- and macronutrients were higher than the control tissue levels. The elevated concentrations were determined to be a consequence of sludge additions and plant growth in a restricted volume of soil.

- The EPC test was a good predictive tool for lettuce growth. Soil EPC levels were shown to affect the lettuce yields. Pots with an EPC < 0.5 mg P/kg soil had a significantly lower yield.

- Soil EPC decreased with sludge additions. The binding of soluble phosphorus, caused by sludge additions to soil, was found to be a problem. The fresh sludge additions to the pot soil caused a severe EPC deficiency and resulted in a decreased yield.

Radish pot study conclusions

- The addition of aged sludge improved radish leaf and root dry matter yields. The highest yield was produced in the 8% aged sludge treatment. The fresh sludge treatment produced the lowest radish yields.

- Only the aluminum and copper concentrations increased in the sludge treated pots. The other elements analyzed were similar to the control soil levels.

- Radish tissue phosphorus concentrations were reduced in the plants grown in soil which received sludge additions.

- EPC was a good predictive tool for determining potential P deficiency for radish growth. Soil EPC concentrations in the pots treated with aged sludge were sufficient for good radish growth. The fresh sludge soil EPC was < 0.5 mg P/kg soil, and produced a significantly lower yield.

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Appendix A

Table A-1

Background elemental analysis for the wheat field soil used in the WTR land application study.

Residual Treatmen	Mn	Al	Zn	Cu	S	Fe	K	Mg	Ca	P
	ppm						%			
Control	30.9 b	473 abc	1.14 a	1.80 a	11.2 ab	176 a	0.83 ab	2.07 a	6.35 a	0.39 a
PACl (x)	34.5 b	530 ab	1.30 a	2.06 a	12.7 ab	174 a	0.58 b	1.92 a	6.40 a	0.33 a
PACl (2x)	30.6 b	405 c	1.08 a	1.56 a	9.9 b	130 ab	0.78 ab	1.52 a	5.43 a	0.35 a
Alum	52.3 a	543 a	1.10 a	1.94 a	9.3 b	116 b	0.88 a	1.91 a	6.07 a	0.37 a

* - Values within columns followed by the same letter are not statistically different at 0.05 level of significance.

Table A-2

Elemental analysis data for the wheat field soil after the application of water treatment residuals and fertilizers.

Residual Treatment	Mn	Al	Zn	Cu	S	Fe	K	Mg	Ca	P
	ppm						%			
Control	38.6 b	486 c	1.3 d	1.7 b	27.0 ab	195 a	0.89 ab	2.14 a	5.42 ab	0.79 a
PACl (x)	46.0 ab	770 bc	2.7 a	2.1 a	21.8 b	183 a	0.77 b	2.11 a	6.20 a	0.65 a
PACl (2x)	40.1 b	588 bc	2.2 b	1.9 ab	32.0 ab	152 ab	0.89 ab	1.74 a	4.66 b	0.85 a
Alum	60.7 a	1115 a	1.7 c	1.8 b	34.3 ab	124 b	1.04 a	2.18 a	5.83 ab	0.75 a

* - Values within columns followed by the same letter are not statistically different at 0.05 level of significance.

Table A-3

Elemental analysis data for soil collected in the wheat field plots at corn harvest.

Residual Treatmen	Mn	Al	Zn	S	Fe	K	Mg	Ca	P
	ppm					%			
Control	30.6 b	282 d	1.23 c	6.7 c	187 a	0.54 b	2.17 a	6.54 ab	0.89 a
PACl (x)	44.1 ab	657 bc	2.08 a	13.5 abc	159 ab	0.51 b	2.36 a	7.79 a	0.76 a
PACl (2x)	37.9 b	535 c	1.80 ab	9.5 bc	149 b	0.58 ab	1.88 a	5.90 b	1.11 a
Alum	59.4 a	937 a	1.56 ab	17.3 a	115 c	0.67 a	2.33 a	7.27 ab	0.85 a

* - Values within columns followed by the same letter are not statistically different at 0.05 level of significance.

Table A-4

Results of the soil particle size analysis for the wheat field plots before and after WTR additions and at harvest.

Residual Treatment		% Sand	
	Initial	After fertilization	@ Harvest
Control	33.9 a	33.1 a	32.9 a
PACl (1x)	44.2 b	42.3 b	42.2 b
PACl (2x)	29.9 a	30.4 a	29.5 a
Alum	30.9 a	31.3 a	30.0 a

Residual Treatment		% Silt	
	Initial	After fertilization	@ Harvest
Control	50.4 a	50.7 a	50.7 a
PACl (1x)	42.9 b	44.5 b	45.3 b
PACl (2x)	49.7 a	51.6 a	52.5 a
Alum	51.0 a	51.3 a	53.3 a

Residual Treatment		% Clay	
	Initial	After fertilization	@ Harvest
Control	16.1 b	16.3 ab	16.4 ab
PACl (1x)	12.9 c	13.2 b	12.6 b
PACl (2x)	20.5 a	18.1 a	18.1 a
Alum	18.1 ab	17.5 a	16.7 ab

-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

Table A-5

Effective cation exchange capacity of soil collected before and after WTR additions and fertilization.

Residual Treatment	Effective CEC (cmol+/kg)	
	Before	After
Control	16.1 b	16.3 ab
PACl (1x)	12.9 c	13.2 b
PACl (2x)	20.5 a	18.1 a
Alum	18.1 ab	17.5 a

-Values within columns followed by the same letter are not statistically different at 0.05 level of significance according to Duncan's Multiple Range test.

Table A-6

Equilibrium phosphorus concentration of soil collected before and after WTR additions and fertilization, anthesis, and harvest.

Residual Treatment	Equilibrium Phosphorus Concentration (mg/kg)			
	Initial	After fertilization	@ Tasselling	@ Corn Harvest
Control	0.69	1.16	1.69	0.81
PACl (1x)	0.48	1.02	0.86	0.98
PACl (2x)	0.63	0.74	0.65	0.52
Alum	0.43	0.9	0.48	0.5

Appendix B

Table B-1

Wheat field grain and biomass harvest data for individual field plots.

Residual Treatment	Plot #	Grain Moisture %	Total Biomass (kg/ha)	Total Biomass (lb/acre)	Grain Test Weight (g)	Grain Yield (kg)	Grain Yield (lb/acre)	Grain Yield (kg/ha)	Grain Yield (bu/acre)
Control	I4	14.1	9811.0	10998.1	55.8	9.9	5473.6	6135.9	98.1
	II5	15	10920.0	12241.3	56.5	7.3	4036.1	4524.4	71.4
	III3	14.1	11930.0	13373.5	55	11.7	6468.8	7251.5	117.6
	IV2	13.7	13810.0	15481.0	54	12.2	6745.2	7561.4	124.9
PACl (1x)	I2	14.6	11930.0	13373.5	55.7	11.6	6413.5	7189.5	115.1
	II2	14.5	11130.0	12476.7	56.1	11.8	6524.1	7313.5	116.3
	III2	14.1	11660.0	13070.9	56.2	12	6634.7	7437.4	118.1
	IV4	14.3	12150.0	13620.2	55.6	11	6081.8	6817.7	109.4
PACL (2x)	I5	14.4	9749.0	10928.6	55.8	10	5528.9	6197.9	99.1
	II4	14.5	13930.0	15615.5	54.9	11	6081.8	6817.7	110.8
	III5	14.5	10670.0	11961.1	55.6	11.5	6358.2	7127.5	114.4
	IV1	15	14360.0	16097.6	55.6	11.5	6358.2	7127.5	114.4
Alum A	I1	14	13440.0	15066.2	55.6	11.8	6524.1	7313.5	117.3
	II1	14.6	11660.0	13070.9	55.7	11.9	6579.4	7375.5	118.1
	III1	14.9	11160.0	12510.4	56.5	10.7	5915.9	6631.7	104.7
	IV3	14.5	15560.0	17442.8	55.6	11	6081.8	6817.7	109.4
Alum B	I3	14.5	9657.0	10825.5	55.4	11.6	6413.5	7189.5	115.8
	II3	14.5	11320.0	12689.7	53.3	11.8	6524.1	7313.5	122.4
	III4	14.1	13130.0	14718.7	55.7	11.5	6358.2	7127.5	114.2
	IV5	15.1	12890.0	14449.7	55.3	9.9	5473.6	6135.9	99.0
Plot averages									
Control		14.2	11617.8	13023.5	55.3	10.3	5680.9	6368.3	103.0
PACl (1x)		14.4	11717.5	13135.3	55.9	11.6	6413.5	7189.5	114.7
PACl (2x)		14.6	12177.3	13650.7	55.5	11.0	6081.8	6817.7	109.6
Alum A		14.5	12955.0	14522.6	55.9	11.4	6275.3	7034.6	112.4
Alum B		14.6	11749.3	13170.9	54.9	11.2	6192.3	6941.6	112.8

Table B-2

Wheat seed, stem and head weight analysis data for individual field plots.

Residual Treatment	Plot #	No. of Plants Sampled	Total Stem Weight (g)	Total Head Weight (g)	Average Stem Weight (g)	Average Head Weight (g)	Total Seed Weight (g)	Average Seed weight per head (g)
Contol	I-4	20	4.12	31.54	0.21	1.58	26.13	1.31
	II-5	19	6.89	30.71	0.36	1.62	25.83	1.36
	III-3	19	4.46	32.74	0.23	1.72	27.82	1.46
	IV-2	23	9.09	42.18	0.40	1.83	34.87	1.52
PACl(1x)	I-2	20	4.03	32.12	0.20	1.61	27.22	1.36
	II-2	22	7.95	42.48	0.36	1.93	36.21	1.65
	III-2	20	5.34	34.02	0.27	1.70	28.52	1.43
	IV-4	23	8.55	40.27	0.37	1.75	33.89	1.47
PACl (2x)	I-5	20	4.25	31.51	0.21	1.58	27.2	1.36
	II-4	26	10.54	45.25	0.41	1.74	37.43	1.44
	III-5	20	5.37	32.78	0.27	1.64	27.41	1.37
	IV-1	21	8.44	39.32	0.40	1.87	33.01	1.57
Alum A	I-1	20	3.4	38.78	0.17	1.94	32.04	1.60
	II-1	21	6.41	40.27	0.31	1.92	32.84	1.56
	III-1	20	4.18	35.95	0.21	1.80	30.05	1.50
	IV-3	25	7.76	48.45	0.31	1.94	39.28	1.57
Alum B	I-3	20	3.8	32.87	0.19	1.64	27.57	1.38
	II-3	22	8.45	43.04	0.38	1.96	37.1	1.69
	III-4	20	5.09	32.02	0.25	1.60	26.97	1.35
	IV-5	22	7.13	39.75	0.32	1.81	33.53	1.52

Table B-3

Soil elemental analysis data for the wheat field plots prior to wheat growth.

Residual Treatment	Plot #	Ca	Mg	P	K	Mn	Zn	Fe	Al	Cu	B
		%				ppm					
Control	I4	7.732	2.4012	0.6264	0.4	14.74	1.0336	33.536	153.8	0.5296	0.3032
	II5	6.528	1.9648	0.5448	0.65	10.032	0.9188	74.08	159.16	0.8432	0.2636
	III3	5.972	1.862	0.622	0.5596	12.704	1.0128	41.48	151.12	0.3676	0.2372
	IV2	8.8	3.0292	0.4716	0.5544	17.884	1.03	11.884	162.6	0.3244	0.3296
PACl (1x)	I2	6.948	1.9872	0.5892	0.4836	16.46	1.6352	23.68	263.64	0.6056	0.2636
	II2	6.208	1.8672	0.7096	0.3714	13.92	1.702	28.388	302.48	0.6704	0.1844
	III2	7.092	2.2172	0.7096	0.5592	18.548	1.9172	29.108	307.28	0.5728	0.2372
	IV4	5.76	1.4264	0.6208	0.5468	18.292	1.854	25.004	335.04	0.6272	0.2372
PACL (2x)	I5	8.656	2.3512	0.6184	0.5096	20.384	2.396	26.092	338.44	0.8324	0.3824
	II4	7.28	1.9964	0.6076	0.34064	11.332	2.0588	55.04	392.48	0.9728	0.29
	III5	7.148	1.8752	0.5256	0.393	17.332	2.518	38.02	454.4	0.854	0.29
	IV1	9.152	2.5888	0.4248	0.4144	20.088	1.9592	12.808	381.4	0.5188	0.3692
Alum A	I1	12.824	3.3944	0.6972	0.4412	20.56	1.4712	13.092	550.4	0.508	0.4744
	II1	7.46	2.154	0.5468	0.5652	16.064	0.9324	16.104	622.4	0.5728	0.3296
	III1	8.604	2.5552	0.4696	0.7652	18.256	0.9992	14.7	520	0.7244	0
	IV3	5.796	1.2472	0.4404	0.4016	16.512	0.8904	23.04	654.8	0.508	0.2504
Alum B	I3	6.732	2.0036	0.5024	0.4536	10.8	0.8652	30.74	368.84	0.508	0.29
	II3	6.52	1.968	0.8212	0.4444	11.92	0.9996	37.336	569.6	0.6056	0.2636
	III4	4.472	1.1256	0.4096	0.6472	12.3	0.8148	21.4	681.6	0.454	0.2108
	IV5	6.168	1.7004	0.4432	0.4892	12.912	0.8064	28.904	611.2	0.4972	0.2768

Table B-4

Soil elemental analysis data for the wheat field plots after wheat harvest.

Residual Treatment	Plot #	Ca	Mg	P	K	Mn	Zn	Fe	Al	Cu	B
		%				ppm					
Control	I4	7.488	2.2312	0.474	0.6832	16.38	1.2056	29.764	151.24	1.5076	0.3136
	II5	6.448	1.9156	0.37012	0.6336	10.928	0.9588	76.32	150.76	1.5076	0.2324
	III3	5.044	1.5036	0.35556	0.6996	11.972	0.8884	39.992	138.08	0.7392	0.1972
	IV2	5.396	1.8364	0.19844	0.528	11.832	0.9928	14.932	146.04	0.9696	0.244
PACl (1x)	I2	5.636	1.5992	0.418	0.798	14.58	1.526	19.176	206.64	1.3252	0.2088
	II2	5.012	1.506	0.4364	0.6316	11.84	1.3564	27.44	211.84	1.2384	0.1624
	III2	6.08	1.8948	0.39	0.6804	15.248	1.434	25.092	222.4	0.9984	0.1972
	IV4	4.608	1.1144	0.29584	0.6372	15.656	1.352	21.852	239.2	1.248	0.1856
PACL (2x)	I5	8.188	2.1888	0.36456	0.6876	21.384	2.0988	26.432	264.56	1.9876	0.36
	II4	6.256	1.5596	0.4272	0.5488	11.6	1.728	52.28	299.12	1.248	0.2324
	III5	6.584	1.7548	0.26584	0.534	13.952	1.4496	35.468	260.96	1.1424	0.2672
	IV1	7.52	2.0988	0.24432	0.7124	19.452	1.386	13.524	247.76	0.816	0.3484
Alum A	I1	10.324	2.7664	0.5704	0.8376	22.528	1.5624	13.292	478	1.3252	0.4064
	II1	6.232	1.8368	0.35936	0.7456	15.712	0.972	16.512	466.4	1.1136	0.244
	III1	7.288	2.1532	0.28604	0.8924	19.584	0.904	14.716	450	0.9216	0.2788
	IV3	4.104	1.0636	0.2416	0.7616	12.976	0.952	20.732	512	1.0752	0.2088
Alum B	I3	6.396	1.7992	0.4412	0.88	12.184	1.0044	29.52	342.92	1.1232	0.2672
	II3	6.076	1.7212	0.5424	0.706	12.42	1.1292	40.32	579.6	1.3732	0.2324
	III4	5.44	1.4876	0.2824	0.6176	11.94	0.8632	31.328	376.36	0.9504	0.2324
	IV5	5.152	1.082	0.2768	0.556	15.788	0.8108	19.924	385.12	0.8448	0.2208

Table B–5

Tissue elemental data for wheat leaves collected at anthesis prior to wheat head formation.

Residual Treatment	Plot #	Mn	Al	Zn	Cu	Fe	K	Mg	Ca	N	P
		ppm					%				
Control	I4	80.75	3.75	0.20	0.10	102.55	102.30	23.70	45.90	3.34	29.40
	II5	69.90	3.75	0.20	0.10	122.40	99.60	24.27	40.93	3.23	29.62
	III3	121.85	3.75	0.39	0.10	101.50	101.25	21.96	40.09	3.78	31.49
	IV2	114.10	4.32	3.45	0.10	123.05	136.20	27.35	58.15	3.61	29.70
PACl (1x)	I2	90.05	4.91	0.39	0.10	118.40	90.00	19.50	39.00	3.00	25.50
	II2	96.75	7.12	8.68	0.10	130.05	137.50	24.00	52.50	3.00	26.50
	III2	90.70	4.23	0.20	0.10	92.35	134.00	22.00	43.50	4.00	26.50
	IV4	134.20	3.56	2.35	0.10	106.55	143.00	21.50	49.00	4.00	28.50
PACl (2x)	I5	77.65	3.56	0.82	0.10	100.40	106.50	25.00	44.50	3.00	29.50
	II4	52.10	36.55	0.20	0.10	92.30	98.00	22.50	38.00	3.00	26.00
	III5	84.50	3.37	1.49	0.10	87.15	88.00	24.00	46.00	4.00	26.50
	IV1	117.30	5.87	8.05	0.10	139.95	137.00	25.50	50.50	4.00	29.00
Alum A	I1 WLEV	78.05	6.64	0.48	0.10	128.85	99.00	24.00	44.00	3.00	27.50
	II1	83.60	4.52	0.20	0.10	120.70	150.00	19.50	39.00	3.00	25.50
	III1	97.75	4.91	9.54	0.10	105.00	102.00	22.50	43.50	4.00	28.00
	IV3	106.10	3.27	4.60	0.10	97.35	96.50	20.00	49.50	4.00	25.50
Alum B	I3	86.60	5.19	1.49	0.10	105.20	127.00	21.00	40.50	3.00	28.00
	II3	82.70	3.94	3.36	0.10	114.45	86.50	22.00	38.00	3.00	27.00
	III4	101.45	4.23	0.20	0.10	140.35	172.50	22.50	42.50	4.00	28.50
	IV5	88.20	3.56	1.01	0.10	91.05	108.50	23.50	48.50	4.00	27.00

Table B–6
Tissue elemental data for wheat seeds collected at harvest

Residual Treatment	Plot #	Mn	Al	Zn	Cu	Fe	K	Mg	Ca	N	P
		ppm					%				
Control	I4	33.90	1.25	55.40	1.00	29.85	36.50	12.50	3.00	1.50	33.50
	II5	45.15	1.25	13.20	1.00	36.90	39.00	14.00	30.00	1.40	36.50
	III3	44.90	1.25	13.20	1.00	47.75	39.00	13.50	3.50	1.50	34.00
	IV2	43.40	1.25	15.20	1.00	28.80	39.00	14.50	4.00	1.90	3.50
PACl (1x)	I2	39.80	1.25	7.20	1.00	23.80	38.00	12.50	3.00	1.30	32.50
	II2	39.40	1.25	4.10	1.00	29.70	36.00	12.50	3.00	1.40	32.50
	III2	40.85	1.25	13.35	1.00	28.30	38.50	13.00	3.00	1.70	34.50
	IV4	43.60	1.25	8.50	1.00	22.60	33.50	12.50	3.50	1.70	3.25
PACl (2x)	I5	39.20	1.25	11.10	1.00	30.40	40.00	13.50	3.50	1.50	3.50
	II4	34.75	1.25	6.55	1.00	24.85	36.50	12.50	3.00	1.40	34.00
	III5	44.80	1.25	12.90	1.00	30.85	37.50	12.50	3.50	1.60	33.50
	IV1	39.80	1.25	32.60	1.00	30.60	36.50	12.50	3.00	1.20	32.50
Alum A	I1	33.80	1.25	8.05	1.00	37.20	36.50	12.50	3.00	1.40	32.50
	II1	38.10	1.25	6.40	1.00	22.50	32.00	12.00	3.00	1.60	31.00
	III1	49.80	1.25	11.25	1.00	25.45	38.00	1.35	3.00	1.50	36.50
	IV3	42.80	1.25	11.25	1.00	28.45	37.50	14.00	3.50	1.00	36.50
Alum B	I3	41.00	1.25	7.90	1.00	28.85	38.00	13.50	3.00	1.30	35.00
	II3	40.65	1.25	6.35	1.00	28.70	37.00	13.50	3.50	0.90	35.50
	III4	49.45	1.25	7.40	1.00	26.50	37.00	13.50	3.00	1.60	36.50
	IV5	44.30	1.25	10.50	1.00	25.80	36.50	14.00	4.00	1.70	36.00

Table B-7

Summary of elemental analysis for wheat stem tissue collected at harvest.

Residual Treatment	Ca	Mg	P	N	K	Mn	Zn	Fe	Al	Cu
			%					ppm		
Control	0.20	0.14	0.062	4.16	0.22	64.15	1.1	54.85	3.5	<0.1
PACl (x)	0.22	0.14	0.055	3.96	0.20	70.60	0.2	45.33	3.7	<0.1
PACl (2x)	0.21	0.14	0.047	4.07	0.25	82.65	0.2	48.72	3.7	<0.1
Alum	0.19	0.14	0.070	4.76	0.21	72.40	0.2	49.52	4.0	<0.1

Appendix C

Table C-1

Harvest data for the second lettuce pot study.

Residual Treatment	Total # of plants	Wet leaf weight	Dry leaf weight	Wet weight per plant	Dry weight per plant
Control 1	3	17.09	1.48	5.7	0.49
Control 2	4	20.97	2.14	5.24	0.54
Control 3	5	27.99	3.02	5.6	0.6
Control 4	5	26.25	2.54	5.25	0.51
2% Old 1	4	24.71	1.95	6.18	0.49
2% Old 2	5	27.12	2.01	5.42	0.4
2% Old 3	5	25.52	2.08	5.1	0.42
2% Old 4	4	24.54	2.03	6.14	0.51
4% Old 1	5	25.2	1.86	5.04	0.37
4% Old 2	5	26.95	2.52	5.39	0.5
4% Old 3	5	29.16	2.28	5.83	0.46
4% Old 4	5	33.46	3.08	6.69	0.62
8% Old 1	5	32.64	2.37	6.53	0.47
8% Old 2	7	33.09	2.41	4.73	0.34
8% Old 3	5	24.86	1.94	4.97	0.39
8% Old 4	4	15.1	0.86	3.78	0.22
4% New 1	5	20.23	1.55	4.05	0.31
4% New 2	5	17.01	1.42	3.4	0.28
4% New 3	5	21.92	1.6	4.38	0.32
4% New 4	5	11.51	0.76	2.3	0.15

Note: All yields are reported in grams.

Table C-2

Radish leaf harvest data for the second radish pot study.

Residual Treatment	Total # of plants	Wet leaf weight	Dry leaf weight	Wet weight per plant	Dry weight per plant
Control 1	5	10.2	1.34	2.04	0.27
Control 2	4	9.94	1.51	2.49	0.38
Control 3	3	5.37	0.82	1.79	0.27
Control 4	3	7.8	1.11	2.6	0.37
2% Old 1	4	12.38	1.64	3.1	0.41
2% Old 2	5	11.73	1.86	2.35	0.37
2% Old 3	4	9.28	1.31	2.32	0.33
2% Old 4	4	8.24	1.23	2.06	0.31
4% Old 1	4	15.74	1.83	3.94	0.46
4% Old 2	4	8.56	1.1	2.14	0.28
4% Old 3	5	11.79	1.74	2.36	0.35
4% Old 4	4	12.55	1.63	3.14	0.41
8% Old 1	3	15.92	1.6	5.31	0.53
8% Old 2	4	19.24	1.93	4.81	0.48
8% Old 3	4	19.51	1.75	4.88	0.44
8% Old 4	5	18.63	1.85	3.73	0.37
4% Fresh 1	5	6.87	0.58	1.37	0.12
4% Fresh 2	3	5.44	0.65	1.81	0.22
4% Fresh 3	4	6.72	0.73	1.68	0.18
4% Fresh 4	4	4.48	0.58	1.12	0.15

Table C-3

Radish root harvest data for the second radish pot study.

Residual Treatment	Total # of plants	Wet leaf weight	Dry leaf weight	Wet weight per plant	Dry weight per plant
Control 1	5	20.41	1.66	4.08	0.33
Control 2	4	19.53	1.61	4.88	0.4
Control 3	3	14.67	1.14	4.89	0.38
Control 4	3	16.17	1.39	5.39	0.46
2% Old 1	4	14.52	1.34	3.63	0.34
2% Old 2	5	10.08	1.29	2.02	0.26
2% Old 3	4	12.82	1.33	3.21	0.33
2% Old 4	4	15.15	1.53	3.79	0.38
4% Old 1	4	25.13	2.45	7.03	0.61
4% Old 2	4	16.49	1.38	4.12	0.35
4% Old 3	5	8.17	1.07	1.63	0.21
4% Old 4	4	19.1	1.62	4.78	0.41
8% Old 1	3	26.16	2.03	8.72	0.68
8% Old 2	4	24.53	2.26	6.13	0.57
8% Old 3	4	35.85	2.65	8.96	0.66
8% Old 4	5	28.93	2.37	5.79	0.47
4% Fresh 1	5	12.96	0.89	2.59	0.18
4% Fresh 2	3	9.9	0.76	3.3	0.25
4% Fresh 3	4	10.21	0.98	2.55	0.25
4% Fresh 4	4	9.81	0.79	2.45	0.2

Appendix D

Table D-1

Summary of the statistical analysis for lettuce and radish 48 hour water loss and yield for the first pot study.

Residual Treatment	Average 48 hour Water loss	Fresh Leaf Weight	Fresh Root Weight	Dry Leaf Weight	Dry Root Weight
Lettuce pots					
Control	190 a	6.38 c	0.69 b	0.37 b	0.07 ab
2% Old	212 a	7.90 b	1.05 a	0.46 ab	0.10 a
4% Old	184 a	10.28 a	0.82 ab	0.50 a	0.08 ab
8% Old	157 a	8.46 b	0.91 ab	0.40 b	0.08 ab
4% New	201 a	4.01 d	0.34 c	0.39 b	0.06 b
Radish pots					
Control	207 ab	3.56 a	7.91 a	0.33 a	0.59 ab
2% Old	223 a	4.28 a	9.44 a	0.35 a	0.71 a
4% Old	216 ab	4.80 a	7.83 a	0.39 a	0.59 ab
8% Old	133 c	4.99 a	9.27 a	0.40 a	0.69 a
4% New	184 b	2.40 c	4.60 b	0.24 b	0.41 b

* - Values within columns followed by the same letter are not statistically different at 0.05 level according to Duncan's Multiple Range test

Note: Water loss is reported as grams/pot, yield is in grams/plant.

Table D-2

Radish and lettuce harvest data for the first pot study.

Residual Treatment	No. Plants per pot	Wet leaf Weight	Wet root Weight	Dry leaf Weight	Dry root Weight	Average Wet leaf Weight	Average Wet root Weight	Average Dry leaf Weight	Average Dry root Weight
Lettuce pots									
Control 1	10.00	57.74	8.61	3.73	0.65	5.77	0.86	0.37	0.07
Control 2	8.00	57.44	4.51	3.07	0.50	7.18	0.56	0.38	0.06
Control 3	9.00	60.38	6.39	3.34	0.59	6.71	0.71	0.37	0.07
Control 4	8.00	46.92	4.88	2.82	0.50	5.87	0.61	0.35	0.06
2% Old 1	9.00	59.37	6.56	3.08	0.88	6.60	0.73	0.34	0.10
2% Old 2	8.00	70.10	9.60	4.42	0.93	8.76	1.20	0.55	0.12
2% Old 3	8.00	67.33	9.40	3.95	0.63	8.42	1.18	0.49	0.08
2% Old 4	8.00	62.44	8.77	3.75	0.85	7.81	1.10	0.47	0.11
4% Old 1	8.00	67.15	4.91	3.17	0.40	8.39	0.61	0.40	0.05
4% Old 2	7.00	65.84	5.41	3.39	0.41	9.41	0.77	0.48	0.06
4% Old 3	5.00	60.50	5.39	3.00	0.66	12.10	1.08	0.60	0.13
4% Old 4	5.00	55.87	4.00	2.66	0.28	11.17	0.80	0.53	0.06
8% Old 1	7.00	61.18	6.30	3.10	0.61	8.74	0.90	0.44	0.09
8% Old 2	6.00	57.18	6.37	2.59	0.59	9.53	1.06	0.43	0.10
8% Old 3	8.00	66.60	6.95	3.19	0.62	8.33	0.87	0.40	0.08
8% Old 4	9.00	65.06	7.42	2.86	0.34	7.23	0.82	0.32	0.04
4% New 1	8.00	32.13	2.89	2.99	0.41	4.02	0.36	0.37	0.05
4% New 2	8.00	33.47	2.47	3.10	0.42	4.18	0.31	0.39	0.05
4% New 3	8.00	35.87	2.94	3.78	0.56	4.48	0.37	0.47	0.07
4% New 4	8.00	26.86	2.65	2.53	0.45	3.36	0.33	0.32	0.06
Radish pots									
Control 1	5.00	16.01	45.55	1.71	3.36	3.20	9.11	0.34	0.67
Control 2	6.00	18.69	41.53	2.05	3.07	3.12	6.92	0.34	0.51
Control 3	6.00	19.05	46.10	1.68	3.54	3.18	7.68	0.28	0.59
Control 4	6.00	23.53	47.63	2.07	3.41	3.92	7.94	0.35	0.57
2% Old 1	6.00	24.69	56.60	1.86	4.00	4.12	9.43	0.31	0.67
2% Old 2	5.00	27.03	59.01	2.19	4.30	5.41	11.80	0.44	0.86
2% Old 3	7.00	26.13	50.92	2.18	4.00	3.73	7.27	0.31	0.57
2% Old 4	6.00	23.02	55.53	1.91	4.45	3.84	9.26	0.32	0.74
4% Old 1	7.00	34.15	36.68	2.87	2.40	4.88	5.24	0.41	0.34
4% Old 2	8.00	35.87	49.95	2.95	4.17	4.48	6.24	0.37	0.52
4% Old 3	6.00	27.40	58.72	2.14	4.68	4.57	9.79	0.36	0.78
4% Old 4	6.00	31.52	60.30	2.54	4.32	5.25	10.05	0.42	0.72
8% Old 1	6.00	27.25	65.80	2.19	4.61	4.54	10.97	0.37	0.77
8% Old 2	6.00	35.02	51.32	2.53	3.73	5.84	8.55	0.42	0.62
8% Old 3	6.00	32.48	50.31	2.68	4.22	5.41	8.39	0.45	0.70
8% Old 4	6.00	24.95	54.90	2.02	4.06	4.16	9.15	0.34	0.68
4% New 1	6.00	11.59	17.58	1.21	1.62	1.93	2.93	0.20	0.27
4% New 2	6.00	14.94	27.67	1.44	2.45	2.49	4.61	0.24	0.41
4% New 3	6.00	16.69	37.90	1.60	3.21	2.78	6.32	0.27	0.54
4% New 4	6.00	14.35	27.18	1.39	2.42	2.39	4.53	0.23	0.40

Note: All yields are reported in grams.

Table D-3

Water loss data for the first pot study.

	Lettuce pots				Radish pots			
Residual Treatment	48 hour Water loss Sample 1	48 hour Water loss Sample 2	48 hour Water loss Sample 3	Average 48 hour loss	48 hour Water loss Sample 1	48 hour Water loss Sample 2	48 hour Water loss Sample 3	Average 48 hour loss
Control 1	165	275	280	240	140	210	225	192
Control 2	180	2	250	144	200	175	200	192
Control 3	160	235	240	212	210	255	265	243
Control 4	100	185	200	162	170	210	220	200
2% Old 1	165	290	300	252	220	200	205	208
2% Old 2	160	225	250	212	190	270	285	248
2% Old 3	130	225	235	197	190	230	245	222
2% Old 4	205	235	220	220	170	235	240	215
4% Old 1	70	270	280	207	210	225	235	223
4% Old 2	160	195	205	187	220	235	240	232
4% Old 3	160	185	200	182	170	210	230	203
4% Old 4	120	175	185	160	220	185	210	205
8% Old 1	80	90	100	90	40	160	185	128
8% Old 2	180	190	195	188	30	160	175	122
8% Old 3	160	180	190	177	40	160	180	127
8% Old 4	130	190	195	172	30	215	220	155
4% New 1	180	230		205	115	190		153
4% New 2	190	240		215	160	250		205
4% New 3	190	220		205	185	230		208
4% New 4	165	190		178	150	185		168

Note: Water loss is reported in grams / pot.

Table D-4

Lettuce and radish pot soil elemental analysis data from the first pot study.

Residual	Ca	Mg	P	K	Mn	Zn	Fe	Al	Cu	B
Treatment			%				ppm			
Lettuce Control	7.84	2.42	0.74	0.46	46.08	3.1672	38.86	198.36	0.5188	0.4216
Lettuce 4% New	8.54	2.67	0.77	0.49	35.024	4.972	33.844	485.6	0.6704	0.4084
Lettuce 2% Old	8.1	2.45	0.73	0.36	55.52	2.6072	43	348.56	0.6056	0.448
Lettuce 4% Old	7.91	2.38	0.76	0.36	39.412	2.8304	33.748	295.8	0.5728	0.4876
Lettuce 8% Old	8.12	2.41	0.69	0.33	45	3.2548	35.164	554.4	0.7784	0.4348
Radish Control	7.8	2.41	0.69	0.42	37.996	3.1884	32.872	178.04	0.4324	0.4876
Radish 4% New	8.31	2.6	0.73	0.67	33.892	4.04	37.264	453.2	0.5944	0.4084
Radish 2% Old	8.15	2.49	0.73	0.34	34.272	2.6368	33.716	268.16	0.5188	0.448
Radish 4% Old	8.6	2.55	0.78	0.33	40.88	2.97	35.04	347.6	0.61	0.43
Radish 8% Old	8.15	2.41	0.66	0.34	42.56	3.36	34.19	469.6	0.68	0.5

Table D-5

Lettuce and radish tissue elemental analysis data from the first pot study.

Residual Treatment	S	Mn	Al	Zn	Cu	Fe	K	Mg	Ca	N	P
	ppm						%				
Lettuce leaf											
Control	43.360	0.743	1.928	0.412	0.002	19.420	5.32	0.86	1.60	2.40	0.91
4% New	32.100	0.726	1.331	0.435	0.002	7.259	4.79	0.63	1.32	1.68	0.51
2% Old	36.730	2.318	2.721	0.420	0.002	14.960	4.27	1.07	1.59	2.37	0.69
4% Old	47.100	1.453	2.651	0.656	0.002	13.690	4.62	1.45	2.04	2.82	0.86
8% Old	51.320	1.316	2.844	0.884	0.002	14.970	4.83	1.58	2.25	3.86	0.67
Radish leaf											
Control	47.040	1.035	1.413	0.669	0.002	7.242	5.22	1.59	4.90	2.27	1.03
4% New	167.300	0.492	0.431	0.578	0.002	2.675	5.86	1.79	4.83	2.25	0.69
2% Old	126.800	0.944	1.309	0.456	0.002	7.471	4.80	1.96	4.88	2.72	0.77
4% Old	109.100	1.107	1.471	0.304	0.002	7.044	4.42	1.87	4.95	2.72	0.56
8% Old	132.2	0.881	1.89	0.303	0.002	9.218	3.72	2.19	5.15	3.12	0.44
Radish root											
Control	41.010	0.480	1.834	0.345	0.002	8.589	4.44	0.43	0.78	1.24	1.07
4% New	99.470	0.220	0.906	0.297	0.002	4.206	4.42	0.43	0.72	1.22	1.02
2% Old	71.180	0.287	1.315	0.218	0.002	6.340	4.41	0.37	0.63	1.22	0.87
4% Old	71.720	0.581	3.528	0.321	0.002	17.320	4.36	0.38	0.62	1.31	0.81
8% Old	85.500	0.447	2.175	0.337	0.002	10.690	4.03	0.45	0.67	1.34	0.64

Vita

The author was born in Fairfax, Virginia on January 13, 1970. He later moved to Tabb, Virginia where he attended Tabb High School and graduated in 1988. He received his B.S. in Biology at VPI&SU in 1993. Upon graduation from VPI&SU he immediately entered the Environmental Engineering graduate program at VPI&SU. Upon completion of his Masters degree in March of 1994 the author accepted a engineering position with Environmental Engineering & Technology in Newport News, Virginia. He immediately found himself traveling the countryside in a mobile lab unit conducting water treatment research.

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