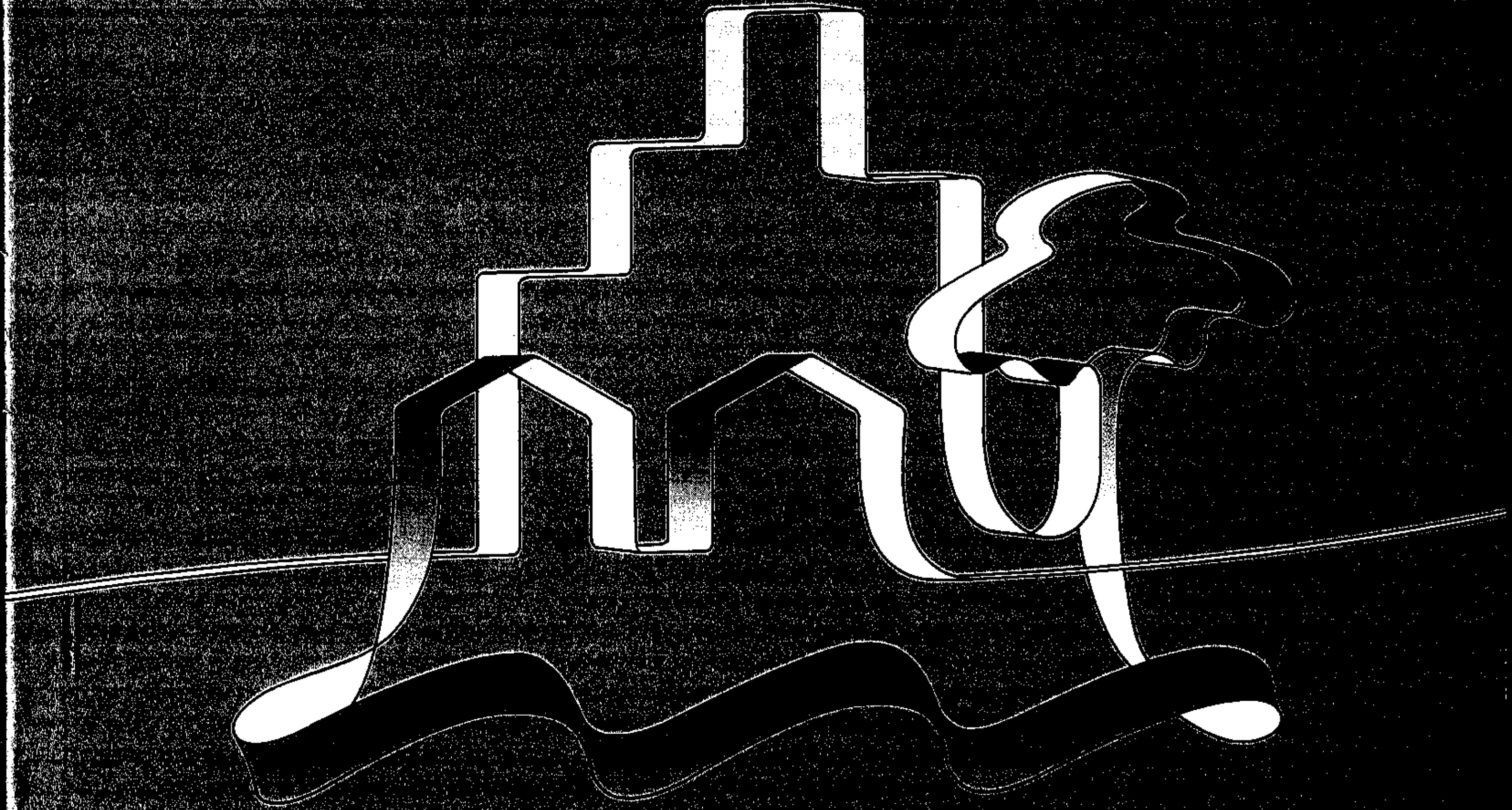
Urban Water Research Association of Australia

Water Treatment Sludge: Potential for Use as a Soil Ameliorant



Research Report No. 106

URBAN WATER RESEARCH ASSOCIATION OF AUSTRALIA (UWRAA)

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For further details contact:
Dr John Langford
Executive Director
Water Services Association of Australia
Level 7
469 Latrobe Street Telephone: (03) 9606 0678
Melbourne Vic 3000 Fax: (03) 9606 0376

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Water Treatment Sludge: Potential for Use as a Soil Ameliorant

M Ahmed, C D Grant, Dept of Soil Science
J M Oades, Waite Agricultural Research Institute
The University of Adelaide

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FOREWORD

This report is based on UWRAA Research Project No WS-69: 'Water Treatment Sludge: Potential for Use as a Soil Ameliorant' which was undertaken during the period June 1994 - June 1996. Organisational responsibility for the project was as follows:

Sponsoring Authority:	South Australian Water Corporation
Project Officer:	Dr Mustaque Ahmed University of Adelaide, Waite Agricultural Research Institute Glen Osmond, South Australia
Research Agency:	University of Adelaide, Waite Agricultural Research Institute
Principal Researcher:	Professor J M Oades University of Adelaide, Waite Agricultural Research Institute

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Summary

This report outlines the investigations conducted between 1993 and 1996 to identify the potential for water treatment sludges, which are subject to stringent EPA guidelines with respect to handling and disposal, to be used as a soil ameliorant in preference to dumping it in municipal landfill sites. Before the sludge can be utilised in an unregulated manner, however, it was necessary to establish whether it had any physical or chemical properties that might pose an environmental health hazard when released. While there was no evidence in the literature of any such problems, much of the literature was from overseas, and thus applicable to different soils and environmental conditions. It was considered necessary to establish up-to-date local evidence to govern the disposal of sludges generated in Australia. The four objectives of the project were therefore to 1) determine the magnitude of soluble aluminium in alum sludge in comparison with naturally occurring soils, 2) determine the magnitude of soluble aluminium in an acidic soil at the Waite Research Institute with and without sludge and lime in various proportions, 3) determine the effects of adding sludge to soils in different proportions on the establishment and growth of lawn grasses, and 4) evaluate the utility of sludge as an ingredient in commercial potting mixes.

In all laboratory, glasshouse and field experiments, the sludge was found to possess no serious detrimental properties, and in particular no soluble aluminium by comparison to other natural soils in Australia. On the contrary, a number of beneficial properties were identified, including low bulk density, high infiltration rate, plenty of available nitrogen, a neutral to alkaline pH, and a modest calcium carbonate equivalence. When mixed as a potting ingredient with sand and other materials, the sludge imparted favourable properties when compared with commercially available mixes. Plant yields from sludge and from sludge-based mixes were as high or higher than those in just soil. The main agronomic limitation of the sludge was its large P-fixing capacity, which necessitated large quantities of added P-fertiliser. From an environmental viewpoint, however, this could be regarded as an advantage, as the sludge might be used to remove P from contaminated water sources; further research to quantify its effectiveness is being planned. In short, once the sludge has been air dried, its disposal need not be stringently regulated and can be safely used in many ways, only a few of which have been identified here (eg. to raise soil pH of acidic soils, or as a potting mix ingredient).

1. Introduction

1.1 Background

Water filtration plants in South Australia produce drinking water by treating 'raw' water from the River Murray and from catchment reservoirs. The treatment process involves flocculation and filtration of the suspended clays and dissolved organic compounds using either aluminium sulphate (alum), ferric chloride, poly electrolytes, activated carbon, or a combination of these (Lehmann and Palmer, 1995). The flocculated material, commonly known as *sludge*, is de-watered either by evaporation from shallow lagoons, or where space is limited, by using mechanical presses before partial drying in concrete holding bays. The sludge is then considered to be an industrial waste, and is thus disposed of, generally in regulated landfill sites.

The quantity of sludge produced depends upon the municipal demand for water, and is therefore greatest at filtration plants near urban areas and during hotter months of the year. For example, the Happy Valley water treatment plant near Adelaide, SA, annually produces in excess of 10,000 tonnes of sludge (25% dry solids), and at present, most of this is disposed of in municipal landfill dumps at a cost to the State estimated conservatively at $120,000 pa (Lehmann and Palmer 1995). Moreover, the landfill disposal option is becoming increasingly problematic as suitable sites for disposal come under pressure for urban development; an internationally acknowledged problem (eg. Elliott and Dempsey 1991).

It has been suggested, on the basis of numerous studies (e.g. Rengasamy *et al.* 1980; Bugbee and Frink 1985; Grabarek and Krug 1987), that the physical and chemical properties of water treatment sludges make them suitable for use as a soil ameliorant rather than simply for disposal as a waste product. For example, because of the high content of calcium carbonate in alum sludges (added to raise pH of water to precipitate soluble aluminium compounds) these sludges are commonly used in the United States as a substitute for lime, and no phytotoxic effects (which might be expected if soluble forms of aluminium were to be produced) have yet been associated with their use on land (eg. Elliott and Singer 1988; Geertsema *et al.* 1994). Unlike sewage sludges and other industrial wastes, water filtration sludges contain few, if any, contaminants (Geertsema *et al.* 1994). When contaminants do occur they are usually associated with the raw water itself, which may contain, for example, copper sulphate - added during some summers to control algal growth in reservoirs (Lucas *et al.* 1994). The amount of copper in sludges thus varies, but is usually small and below the acceptable upper limits established by US-EPA standard procedures (Grabarek and Krug 1987). Contaminants may also occur as impurities (eg. heavy metals) in the coagulants used, but these metals are generally found in such low concentrations as to be nonbioavailable and virtually immobile in most soils, particularly at modestly alkaline pHs (Elliott *et al.* 1990).

There would thus appear to be considerable potential for land-based disposal of water treatment sludges under certain conditions. If, for example, it could be shown that application of water treatment sludges to land represented an environmentally safe and economically viable option in Australia, this would represent a significant advance. The costly and problematic disposal issue would be neatly solved, and the future demand for this material might even outstrip its supply (Skene and Oades 1995). Nevertheless, because the soil environment in which the sludge could be released varies enormously across the Murray-Darling Basin, a range of different soil types needs to be examined in conjunction with appropriate agronomic research to test the applicability of conclusions drawn from research overseas conducted on very different soils.

2 Aims

2.1 Original aims

In order to explore the land-based options for disposal of water treatment sludges produced in South Australia, a collaborative study was proposed by the Engineering and Water Supply Department of South Australia and the Department of Soil Science of the University of Adelaide.

The original aims of this study were twofold:

1) to assess the potential for using water treatment sludge as an ameliorant on sandy vineyard soils, and for the preparation of recreational areas, especially lawns and ornamental gardens. (It was thought that the high clay and organic matter contents of the sludge would improve soil structure,

increase water and nutrient holding properties, and thus increase plant growth and productivity on amended soils) and,

2) to determine whether sludge, and sludge-amended soils, might become potential sources of phytotoxic aluminium in the environment with time. (On the basis of preliminary results from laboratory techniques that use highly acidic extraction procedures, there was a perception that a potential hazard might exist if the sludge were to be applied to acidic soils).

2.2 Revised aims

Because water treatment sludges and sewage sludges in Australia are classified by the Environmental Protection Authority (EPA) as 'industrial wastes'; these are subject to stringent disposal regulations. Official EPA approval is thus required to transport sludges from production plants. Because the South Australian EPA did not want the sludge to be released onto private land before the issue of possible aluminium mobility and phytotoxicity was clarified (*cf.* Cugley 1994), approval to cart sludge to selected vineyards near Adelaide was not granted. Two public sites, however, were approved for transport: (i) the Waite Agricultural Research Institute, and (ii) the disused site of the old Hackney Bus Depot adjacent the Royal Botanical Gardens, the city of Adelaide. Of these two sites, only the Waite Institute was suitable for controlled experimental work, so for all intents and purposes, the nature of the research that could be planned was severely restricted*.

The aims of this project were therefore revised to focus primarily on the aluminium issue, and to explore potential uses of the sludge where its dispersal in large quantities could be limited (e.g. in the potting mix industry). The revised aims, (which encompass the original aims to a large extent) were therefore to:

1) determine the concentration of soluble aluminium species from the sludge in comparison with a range of naturally occurring Australian soils,

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*** Sludge at the Hackney site was used primarily as landfill and has been vegetated with lawn grass, which has flourished. (P. Matthews, Senior Curator Royal Botanical Gardens Adelaide, Pers. Com.)**

2) determine the concentration of soluble aluminium in the (acidic) Waite Institute soil with and without the addition of alum sludge and lime in various proportions.

3) determine the effects of adding alum sludge to soils in different proportions on the establishment and growth of lawn grasses.

4) evaluate the utility of alum sludge as an ingredient in commercial potting mixes used in horticultural industry.

To achieve these aims, several laboratory and glasshouse studies, plus a small field study were embarked upon at the Waite Institute, and these will be outlined in the **Materials and methods** section 4. Before these studies were initiated, however, the literature was examined to establish what was known about i) the physical and chemical properties of water treatment sludge, ii) the implications these properties might have for experimental measurements required and iii) how land might best be managed once sludge was applied. The following sections summarise this literature.

3. Literature review

3.1 Properties of water treatment sludge and implications for land disposal

To a large extent, the physical and chemical properties of water treatment sludges depend upon the coagulants and carbonates used in their preparation (eg. alum, ferric chloride, activated carbon, polymers, lime etc.), plus the nature of the dissolved and suspended matter removed from the raw water. For example, the pH of alum sludges can range from 5.1 up to 8.0 depending upon the amount of lime ($CaCO_3$) added to cause precipitation of soluble species of aluminium (Elliot and Dempsey 1991). Because alum sludges can have a calcium carbonate equivalence of up to 20%, (depending upon their alkalinity) they have an inherent liming value, or pH-neutralising value. This property of water clarification sludges has been appreciated for some time now; in fact, various different types of sludges have been used to raise pH of agricultural soils in the mid western United States over the past 40 - 50 years (*Ibid*). Bugbee and Frink (1985) also found alum sludge applications to a forest soil increased the pH by about 0.5 to 1.0 unit. The magnitude of any increase in pH depends of course on several factors including the original soil pH, the pH of the sludge itself, and the application rate of the sludge.

Alum sludges commonly consist of highly disordered clay minerals plus organic matter and precipitates of aluminium hydroxides (Bugbee and Frink 1985; Rengasamy *et al.* 1980). The aluminium hydroxides are similar in nature to those commonly present in soils (Lucas *et al.* 1994), and may occur in quantities between 3% and 30% total aluminium (Elliot and Dempsey 1991; Rengasamy *et al.* 1980). Total nitrogen content of alum sludges has been found to range from as low as 0.44 - 1.00% (Elliot and Dempsey 1991) to as high as 2.1% (Skene *et al.* 1995). It is generally acknowledged that by comparison with sewage sludges, most alum water treatment sludges are relatively inert with respect to biological pathogens, pesticides, and other organic contaminants (Elliot *et al.* 1990; Grabarek and Krug 1987).

Despite the fact that alum sludge has some highly beneficial properties, advantage of these has generally not been taken, primarily for historical reasons. In Australia, we have followed procedures established in the United States (eg. Kawamura 1991), wherein water filtration sludges and have been classed together with industrial metal hydroxide sludges. The disposal of these materials must adhere to internationally stringent criteria (USC 1980), which generally means they can only be disposed of in prescribed municipal landfill sites.

Concern about alum sludges in Australia appears to centre around their total aluminium content (eg. Cugley 1994; SA EPA 1996). One reason for this may be that aluminium occurs in the natural environment in relatively high concentrations. Next to oxygen and silicon, which comprise 74.3% of elements in the Earth's crust, aluminium is the next most abundant element (8.1%); other elements such as iron, calcium, sodium, potassium, magnesium, each comprise smaller proportions than this (Wild 1993).

Nevertheless, it is generally agreed that for human consumption, the concentration of total aluminium in drinking water should not exceed 200 μg/litre (Sayer 1988). In aquatic environments, the tolerance of various organisms to aluminium is somewhat lower. For example, the toxic limits of concentration for aluminium in fresh and marine waters is approximately 5 μg/litre when $pH < 6.5$, and 100 mg/litre when $pH > 6.5$ (ANZECC 1992). The different concentration limits for

different pHs relate to the fact that the hydrolysis of aluminium in solution is pH-dependent, and certain hydrolysed species are more harmful to biota than others. The most important steps in the hydrolysis reactions in dilute solutions of aluminium are:

Hydrolysis Reaction	**Reaction Constant**
$Al^{3+} + H_2O \leftrightarrow AlOH^{2+} + H^+$	$K_1 = 10^{-4.97}$
$AlOH^{2+} + H_2O \leftrightarrow Al(OH)_2^+ + H^+$	$K_2 = 10^{-4.93}$
$Al(OH)_2^+ + H_2O \leftrightarrow Al(OH)_3^o(aq) + H^+$	$K_3 = 10^{-5.7}$
$Al(OH)_3^o(aq) + H_2O \leftrightarrow Al(OH)_4^- + H^+$	$K_4 = 10^{-7.4}$

When alum ($KAl(SO_4)_2 12H_2O$, or $NH_4Al(SO_4)_2 12H_2O$) dissolves in water it flocculates negatively charged, dissolved or suspended forms of organic and inorganic material; this occurs through the hydrolysis of the aluminium ion to form a gelatinous precipitate of aluminium hydroxide with the charged material. The total concentrations of dissolved species of aluminium in the presence of gibbsite, $Al(OH)_3$, is highly dependent upon pH and reaches a minimum in the range of pHs from 6 to 7 (McBride 1994). For aquatic species, aluminium becomes toxic when pH enters the range 4.4 to 5.4, and is most toxic in the pH range 5.0 to 5.2. Because of its amphoteric nature, aluminium may also become moderately toxic in the alkaline pH range 7 to 9 (Freeman and Evert 1971). The extent of toxicity of aqueous aluminium varies with speciation. The Al^{3+} ion (dominant for $pH < 4.5$) and the simple hydroxides, $Al(OH)^{2+}$ and $Al(OH)_2^+$ (dominant for pHs in the range 4.5 to 6.5), are generally regarded as the most toxic forms of aluminium both to plants (eg. Cameron *et al.* 1986; Bruce *et al.* 1988) as well as to aquatic biota (eg. Alva *et al.* 1986a,b; Driscoll *et al.* 1980). In the pH range 8 to 10, the anionic species dominate and are also phytotoxic (Hesse 1971). Regardless of pH, the organically bound and the polymeric forms are less toxic and considered to be essentially harmless (Hue *et al.* 1986).

While it is generally agreed that information on the various species of aluminium present in soil water can be useful for predicting the consequences of low pH conditions (e.g. Johnson *et al.* 1981), there is less concurrence on the methods that should be used to quantify the various species of aluminium. For example, determination of aluminium in soil extracts by atomic absorption spectroscopy has been found not to differentiate well between soluble and colloidal forms of aluminium nor between labile and non labile soluble complexes. It therefore does not make a good estimate of the toxic fractions of aluminium in soils (Manley *et al.* 1987). Spectrophotometric methods, on the other hand, provide better estimates of the species of aluminium based upon the rates of reaction between various reagents for different periods of time. Among at least four of the spectrophotometric methods currently available, is the pyrocatechol violet method of Dougan and Wilson (1974). Siep *et al.* (1984) used this method (with a reaction time of 4 minutes) to estimate the total concentration of monomeric aluminium, and the pyrocatechol violet method has been relatively widely adopted for the estimation of aluminium in waste water and drinking water (A.P.H.A. 1992). This method will be adopted for all work reported in the present document.

3.2. Land application of water treatment sludges and agronomic effects

Land application of water treatment sludges has been suggested as a potentially effective long term solution to the disposal problem (eg. Skene and Oades 1995), yet only relatively few studies have been conducted to demonstrate the benefits. Rengasamy *et al.* (1980) reported that application of sludge to soils in pots reduced slaking and dispersion, increased soil aggregate stability, and increased moisture retention between the water potentials -10 and -1000 kPa. Application of sludge at 2 t ha^{-1} increased yield of maize (due to improved physical properties and nutrient status), although at the highest application rate (e.g. 20 t ha^{-1}) there were some problems with germination and phosphorus deficiency in the maize plants. Bugbee and Frink (1985) applied alum sludge to a moderately acidic soil in pot experiments and on forested land, and found that sludge raised the soil pH significantly. There were no germination problems found with lettuce and marigold plants, but at higher application rates a serious phosphorus deficiency problem occurred in all plants and this resulted in decreased yields even when P fertilisers were added.

In a separate experiment using smaller sludge application rates, however, Lucas *et al.* (1994) found that P-deficiency problems in fescue grasses could be overcome by doubling the application rate of P fertiliser, which also increased plant yield. Geertsema *et al.* (1994) concluded that alum sludges

may be applied to forest lands at loading rates of at least 1.5 to 2.5% (dry weight basis) without negative effects. Furthermore, 30 months after sludge application, there was no evidence of any migration of metal elements such as Zn or Cu (minor contaminants in the alum sludge) through soil or ground water.

Skene *et al.* (1995) compared the growth of broad beans in glasshouse pots of sand amended with either alum sludge or alum sludge containing the poly-electrolyte, diallyldimethyl ammonium chloride (polyDADMAC). The sludges were applied to the surface of pots of sand in order to mimic a field trial (*cf.* Skene *et al.* 1994) in which the effects of water treatment sludge on the establishment of cereal ryegrass on sand dunes were examined. In the pot trial, dry matter production of the broad beans was greater in the polyDADMAC sludge treatments than in the alum sludge treatments, and the difference was attributed primarily to the presence of phosphorus, nitrogen and potassium in the polyDADMAC sludge (all constituents of the poly-electrolyte). The main advantages of using the sludge as a growth medium for plant growth were attributed to an improvement in physical properties: increased water holding capacity, improved drainage characteristics and greater structural stability. Of particular importance with respect to the issue of aluminium mobility and toxicity to plants was that the broad bean plant tissue from the treatments with the highest application rates of alum sludge contained significantly lower aluminium than the plant tissue from the control soil to which no alum sludge was added. Skene *et al.* (1994) also demonstrated that a wide range of vegetable crops grew satisfactorily on beds of sludge in the field, and that plant tissue analysis did not reveal the presence of any elements detrimental to human health.

4. Materials and methods

4.1 Introduction

Four main experiments were conducted to achieve the **Revised aims** stated in Section 2.2. The initial work was conducted to characterise the physical and chemical properties of the alum sludge deemed important from an agronomic standpoint (*cf.* Section 4.3). Another experiment involved the comparison of soluble aluminium in alum sludge with that in different soils from across Australia (*cf.* Section 4.4). A third study involved both glasshouse and field trials designed to examine the agronomic effects of adding sludge to a soil (*cf.* Section 4.5). The final study was conducted to evaluate the use of water treatment sludge as an ingredient in potting mixes by comparison with several commercially available products (*cf.* Section 4.6).

4.2 Collection and pretreatment of alum sludge

Several tonnes of alum sludge from the Happy Valley water filtration plant near Adelaide, South Australia were collected from the concrete holding bay at the de-watering plant, and transported to the Waite Agricultural Research Institute to be stockpiled for use in all experiments (see **Appendix** photos). Because the sludge existed in relatively large chunks when it left the de-watering plant, it needed to be broken into smaller pieces, and this was done in various ways depending upon the experimental purpose. For laboratory investigations, for example, sludge was dried at 40°C for 48 hours, then passed through a 1 mm sieve. For glasshouse experiments, the sludge was wetted and dried 5 times on plastic sheeting in a glasshouse (to promote finer aggregation), then passed through a 5 mm sieve. For the field trials, sludge was simply left outside to wet and dry naturally and turned periodically to promote crumbling it into finer aggregates over a several month period.

4.3 Physical and chemical properties of alum sludge from Happy Valley

To obtain an idea of the porosity and pore sizes in the sludge, water retention at four different matric potentials ranging from Ψ_m = -30 to -1500 kPa were determined using a pressure plate apparatus. Electrical conductivity was determined on samples of solutions having ratio 1:5 sample to water. DTPA extractable Fe, Mn, Cu and Zn were determined by the method of Lindsey and Norvell (1978) and calcium chloride-extractable B was determined by the method of Aitken *et al.* (1987). Available N was determined by the method of Keeney and Nelson (1982), and the P-sorption characteristics were determined by the method of Fox and Kamprath (1970).

4.4 Aluminium in alum sludge and natural soils

Aluminium in the alum sludge was compared with that in nine different soils from across Australia. Mixtures of 1:5 soil or sludge and distilled water or 0.01 M $CaCl_2$ were agitated for one hour on an end-over-end shaker. The pH of the supernatant was determined first after which it was poured onto Whatman No.44 filter paper and then through a 0.2 µm filter. Aluminium in the extracts (hereafter referred to as water soluble aluminium) was determined using the pyrocatechol violet method of Dougan and Wilson (1974).

In a laboratory incubation experiment, the sludge was mixed with one of the nine soils (Urrbrae Red-brown Earth, from the Waite Institute) to produce application rates equivalent to 0, 200, 400, 800, and 1600 t ha^{-1}, assuming a bulk density of 1.2 t m^{-3} (Susanto 1992). Agricultural lime was incorporated into these mixtures at application rates equivalent to 0, 1.8, 3.6, 7.2, and 14.4 t ha^{-1}. Samples of each of these mixtures (20 g) were placed in sealed plastic containers (120 cm^3 capacity) and stored for eight weeks at 20°C at gravimetric water contents corresponding to 0.8 x 'field capacity' as determined for each mixture. At the end of the incubation period, water was added to each sample to make sample-to-water ratios of 1:5, and they were shaken for one hour. Suspensions were analysed for pH and then extracts were taken for determination of water soluble aluminium as described above.

4.5 Effects of alum sludge on performance of lawn grass

4.5.1 Glasshouse study

Sludge was mixed with Urrbrae Red-brown Earth at rates equivalent to 0, 200, 400, 800 and 1600 t ha^{-1}, either by incorporation or by surface application in 10 litre pots. For the treatments to which the sludge was applied on the soil surface, superphosphate fertiliser was pre-mixed with the sludge at a rate of 100 kg P ha^{-1} prior to placing them in the pots. For the treatments to which the sludge was incorporated, superphosphate was mixed together with the soil and the sludge at the same time.

The weight of each pot at "field capacity" was determined as follows: The bases of the pots were fitted with plastic drainage tubes that could be open or shut. The tubes were closed and the pots were saturated for a period of 24 hours, after which the tubes were opened to allow free drainage for a further 24 hours. Weights at this time were deemed to represent "field capacity" and were thus maintained during the first four weeks of the experiment by adding appropriate quantities of water every other day. (After the first four weeks, it was noted that some of the pots may have been too wet, and so to half of the pots, water was subsequently added until the pot weights corresponded to only 60% field capacity, while the rest were watered as before).

Lawn grass seed was sown in all pots at a rate of 237 kg ha^{-1} and the pots were arranged in a randomised complete block design. To minimise differences in growth due to variable temperature and lighting in the glasshouse, the pots were periodically moved to different positions. The experiment lasted 12 weeks after sowing and the grass was harvested 3 cm above the ground surface every 4 weeks during this time. After the first harvest at 4 weeks, all pots received a further application of fertiliser (192 kg N ha^{-1}, 53 kg P ha^{-1}, and 100 kg K ha^{-1}) plus micronutrients according to rates applied by Rengasamy *et al.* (1980) to sludge from the same source. Samples of the lawn grass were dried (70°C for 3 days) to determine dry matter yields, and a subsample of the fresh grass was taken to determine nutrient concentrations in the plant tissue; these subsamples were thoroughly washed in distilled water, dried, ground, then digested in nitric acid for analysis using ICP (Zarcinas *et al.*. 1987).

4.5.2 Field trial

A field experiment was established in a randomised complete block design on Urrbrae Red-brown Earth at the Waite Institute to determine the effect of sludge addition on germination and performance of lawn grass. Sludge was applied at similar rates as for the glasshouse study (Section 4.5.1), but there were no surface applications of the sludge - all of it was incorporated with the soil as follows. Soil was removed from each plot to 20 cm with a front-end loader. Air dry sludge was mixed with this soil in quantities prescribed by the application rates, and the mixtures were placed back into the appropriate plots. Fertiliser was applied to all plots (200 kg P ha^{-1}, 100 kg K ha^{-1}, 10 kg Mn ha^{-1}, 5 kg Zn ha^{-1}, and 0.4 kg Cu ha^{-1}) and incorporated using a rotary hoe. Each treatment was replicated four times in plots having dimensions 3m x 5m and separated from each other by a buffer strip of 1m width. The sludge-soil mixtures in the individual plots were contained by a timber frame around their margins dug into the soil surface (see **Appendix** colour photographs). Rye grass

seeds were sown on all plots at an application rate of 200 kg ha^{-1}, and an automatic sprinkler system was installed to irrigate each plot.

Due to extensive (historical) weed problems on the site, ryegrass had to be sown three times followed by rigorous weed control efforts over a period of several months before satisfactory grass establishment was achieved. Two months after the third sowing all grass was cut to a height of 3 cm using a lawn mower. Harvesting was conducted after an additional 30 days, at which time the total fresh weight of all the grass clippings from each plot was recorded. A subsample of the moist grass clippings was taken from each plot to determine moisture content (dried 70°C) from which dry matter yield was calculated. A second subsample of the moist clippings was taken for tissue analysis for the determination of plant nutrients; this sample was thoroughly washed in de-ionized water, dried and ground prior to analysis using ICP.

When the plots had been established for a total of 14 months, a final dry matter harvest was conducted, and available soil P was determined on each plot by the method of Colwell (1963). Various soil physical properties were also determined on each plot, including infiltration rate using a single ring, bulk density using small cylindrical cores, particle density using pycnometers (Blake and Hartge 1986), total porosity, moisture content at field capacity, and air-filled porosity.

4.6 Evaluation of alum sludge as a potting mix ingredient

The following four materials were used to design 34 different potting mixes: alum sludge, coarse sand, pine bark (< 4 mm, composted), or peat moss (known as 'Euroturf'). The mixes varied according to the proportion by which sludge replaced either the sand or the pine bark/peat moss. Pine bark and peat moss were included as variables in this experiment because these are used in commercially available potting mixes, the pine bark being used in the "regular" grades, and the peat moss being used in the "premium" grades due to it greater water holding properties. The air filled porosity and water holding capacity of each mixture were determined according to the procedures outlined in the Australian Standards for Potting Mixes (Standards Australia 1993), and on the basis of this, the list of potentially acceptable mixes was reduced to six, which were known as Mixes #20,

#25, and #31 with either peat moss or pine bark as the organic component. These were examined in detail for standard physical and chemical properties for commercial potting mixes. All the mixes containing sludge showed low available P, indicating a significant P-fixing capacity of the sludge; it was thus necessary to determine the P-fertiliser requirements for the six mixes. P-fertiliser was therefore applied at rates of 0, 200, 400, 600 and 1200 g P m^{-3}, and the P content of DTPA extracts was determined after 10 days incubation.

The six mixes were evaluated against two commercially available potting mixes, "Nu Erth" and "Peat Soil", by assessing the growth response of marigolds in them. Samples of each potting mix (in 5 litre containers) were fertilised with 5 kg m^{-3} nutricote (20-0-10) plus 700 g m^{-3} iron sulphate. For the two commercial potting mixes, iron was not applied to the mix, but rather as a sprayed iron chelate onto the plant foliage itself, two weeks after planting. Single seedlings of marigold plants were placed into each pot and allowed to grow for 8 weeks in a glasshouse. The experimental design consisted of 5 replications of each treatment in a completely randomised design, wherein the position of the pots was changed regularly to overcome any variability of growth conditions in the glasshouse. After 8 weeks, the plants were harvested and the number of flowers per plant, plus the shoot dry matter yield per plant were recorded.

5. Results and discussion

5.1 Physical and chemical properties of alum sludge from Happy Valley

The alum sludge possessed a high water content at Ψ_m = -30 kPa (simulating "field capacity") and also at Ψ_m = -1500 kPa (simulating "wilting point"). As **Figure 1** and **Table 1** show, there is only a small change in water content between field capacity and wilting point, which indicates the sludge provides little "available" water for plant growth. Similar data on "available" water were also obtained on samples of alum sludge collected independently from Happy Valley in 1996 (S.P. Macks *pers comm.*). The reason for the small available water content is not entirely clear, considering the alum sludge contains so much clay and organic matter (eg. Rengasamy *et al.* 1980), and also since alum sludges collected from other water clarification plants (eg. Morgan Treatment

Table 1. Water content of alum sludge as a function of applied matric potential.

Applied Matric Potential (Ψ_m, kPa)	**Mean Water Content** (kg kg^{-1})
-30	0.548
-100	0.502
-200	0.511
-1500	0.472
	Available Water = 0.074

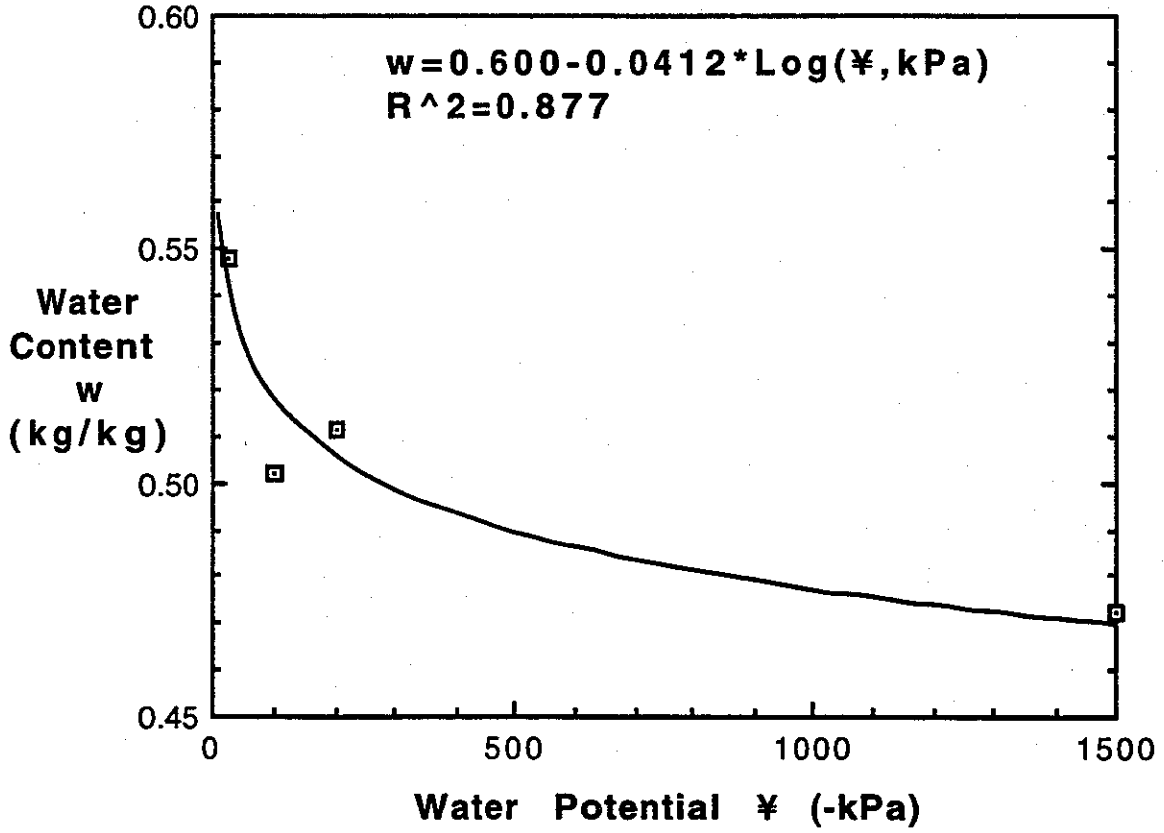

Figure 1. Moisture retention curve for aggregates of alum water treatment sludge

Plant, South Australia) contain significantly higher available water (eg. Skene *et al.* 1995). The result suggests the clarification process at Happy Valley must create pores dominantly in the size range < 0.2 µm. An analysis of the pore size distribution according to Innes (1957) confirms this: the majority of pores in the aggregates of sludge, in fact, were found to be < 10 nm in size. This implies the sludge may not be able to provide sufficient water to support plant growth if the sludge were to be used as the sole rooting medium. If the sludge were to be well mixed with a soil, on the other hand, the available water may be controlled more by the aggregate size distribution of the soil-sludge mixture than by the sludge alone.

Various chemical properties of the alum sludge are presented in **Table 2** in comparison with the Urrbrae Red-brown Earth. While the electrical conductivity data indicate the sludge contains a modest concentration of soluble salts, this poses no serious salinity risk (USSL Staff 1954). Furthermore, the sludge contains at least 5 times more available N (a macro-essential nutrient for plant growth) than does the Urrbrae soil, which has also been found for alum sludges in other studies (eg. Skene *et al.* 1995). While there are fewer DTPA-extractable micronutrients such as B, Fe, Mn, and Zn in the alum sludge relative to the Urrbrae soil, the concentrations are all sufficiently high to accommodate satisfactory plant growth.

Table 2. Chemical properties of alum sludge and Urrbrae Red-brown Earth.

Property	**Alum Sludge**	**Red-brown Earth**
Electrical conductivity (1:5 ratio) (dS m^{-1})	1.1	0.05
Nutrients: (mg kg^{-1})		
Available N	62.3	11.9
B	0.4	1.0
Cu	23.0	2.8
Fe	18.6	56.8
Mn	27.2	50.8
Zn	1.6	6.0

The only micronutrient occurring at an unacceptably high concentrations in the sludge is Cu, and the reason for this is that copper sulphate is sometimes added to water reservoirs to control algal growth. The amount of Cu in alum sludges will thus vary among batches and at different times of year. In any case, it should be noted that simply because the DTPA-extractable copper concentration may be considered to be too high, its bioavailability is not necessarily extreme. The large quantity of organic matter in the sludge may be sufficient to chelate any copper that becomes mobilised with time. The bioavailability of copper from water treatment sludges is certainly worth investigating, particularly if it's presence constitutes the only criteria preventing it from being licensed for disposal on private land or in commercial potting mixes.

As alluded to Section 4.6 with respect to the potting mixes, the sludge appears to have a significant P-fixing capacity. The enormous magnitude of this (by comparison to the P-fixing capacity of the Urrbrae soil) is highlighted in the sorption curves for the two materials shown in **Figures 2a** and **2b**. The quantity of P sorbed at a solution concentration of 10 µg P/ml is two orders of magnitude greater for the sludge than it is for the Urrbrae soil. Considering that the optimum soil solution concentration of P is considered to be 0.2 ppm (Nishimoto *et al.* 1977), the amount of fertiliser P required to achieve this for the alum sludge is inordinately high (11,479 kg P ha^{-1}) by comparison to that required for the Urrbrae soil (18.4 kg P ha^{-1}). The enormous P-fixing capacity of the sludge is comparable in magnitude to that of volcanic ash soils in Alaska, which are rich in amorphous materials (Zagg *et al.* 1979). It has been suggested, however, that the high P-fixing capacity of alum sludges should not be extrapolated directly to the context of land application, as the availability of P is also controlled by soil pH (Elliot and Dempsey 1991). Furthermore, the P that is bound in oxides and hydroxides of aluminium and iron tend to become available to plants that grow slowly (eg. temperate forests), or in situations where the demand for P is relatively small (Grabarek and Krug 1987). Many native Australian plant species would fall into this low-demand, slow growing category.

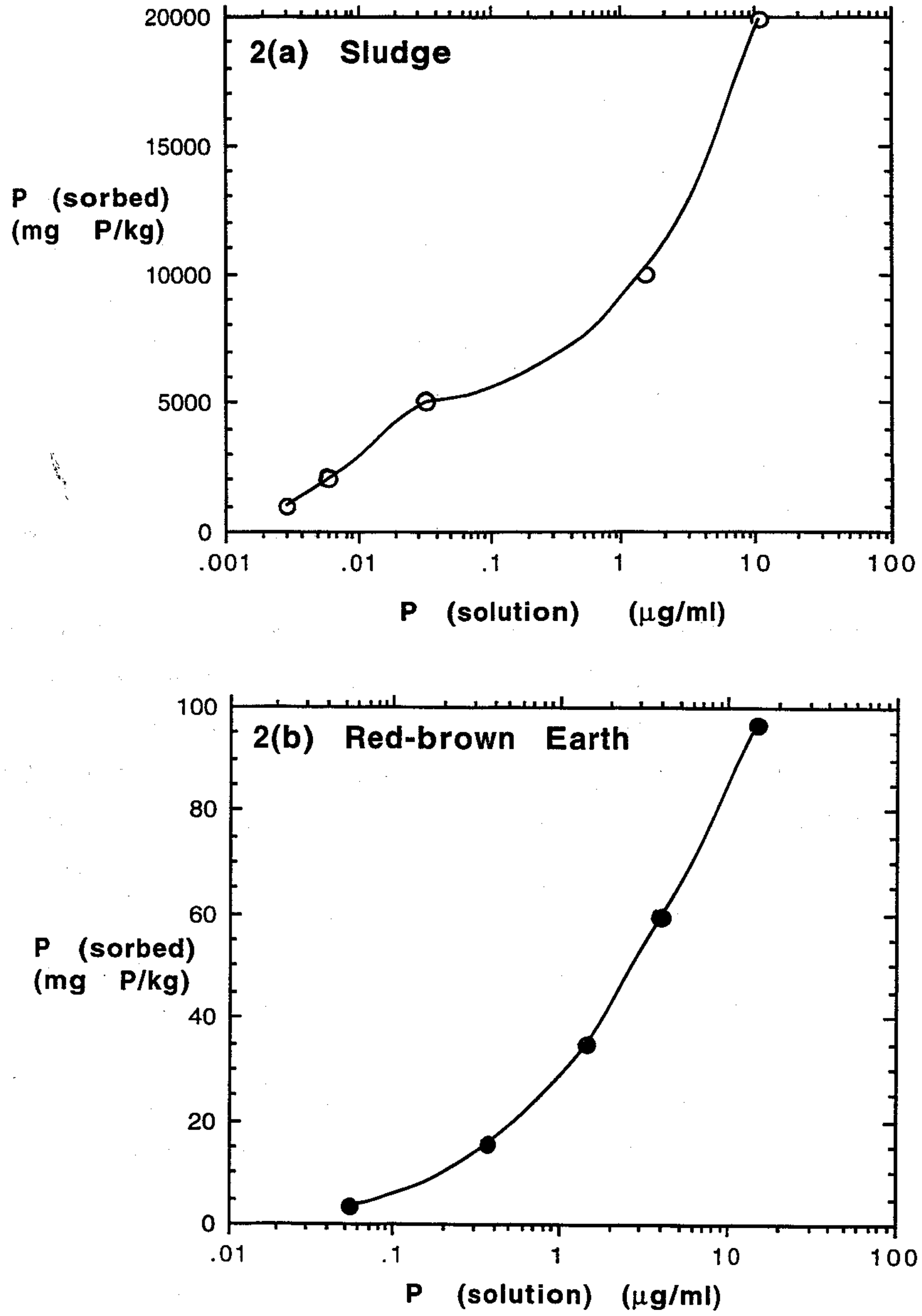

Figure 2. P-sorption curves for a) Alum sludge and b) Urrbrae Red-brown earth.

5.2 Aluminium in alum sludge and natural soils

5.2.1 Comparison with natural soils

A strong, negative relationship was found between the pH of the sludge or soils and the concentration of aluminium in solution (**Table 3; Figure 3**). As is well established in the literature (eg. Oertli 1979) higher concentrations of aluminium were generally found in soils of lower pH. It is of particular importance to note that all the materials having pHs > 6.0 (including the sludge) produced concentrations of aluminium that were virtually negligible, regardless of whether measurements were taken in water or calcium chloride. By comparison with the naturally occurring soils, the sludge presents no phytotoxic risks with respect to aluminium, whereas, without the addition of lime, several of the low-pH soils would present much more significant problems to agricultural plants (eg. Dolling 1989; Whitten and Ritchie 1989).

5.2.2 Effects of sludge and/or lime on pH and aluminium in an acidic soil

The addition of various amounts of alum sludge to the acidic Urrbrae Red-brown Earth caused a significant increase in the pH from 5.7 without sludge up to 7.5 after the addition of 800 to ha^{-1} (**Figure 4**); a calcium carbonate equivalence (or liming value) is clearly demonstrated by the sludge.

Table 3. pH and aluminium concentration in alum sludge and nine soils.

Material	pH (water)	pH ($CaCl_2$)	[Al] (Water)	[Al] ($CaCl_2$)
			(mg kg^{-1})	
Alum Sludge	7.45	7.08	0.54	0.47
Approximate Location of Soil:				
Clarendon, SA	7.51	6.93	0.21	0.12
Gumeracha, SA	5.66	4.88	1.34	1.66
Kuitpo Forest, Meadows, SA	4.94	3.83	1.70	14.8
Millicent, SA	8.19	7.54	0.10	0.22
McLaren Vale, SA	6.30	5.28	0.44	0.23
Mount Bold, SA	6.49	5.50	0.28	2.75
Urrbrae, SA	5.81	4.88	2.91	4.35
QLD	4.21	3.81	7.18	47.4
Dryandra Forrest, WA	5.38	4.79	3.97	5.83

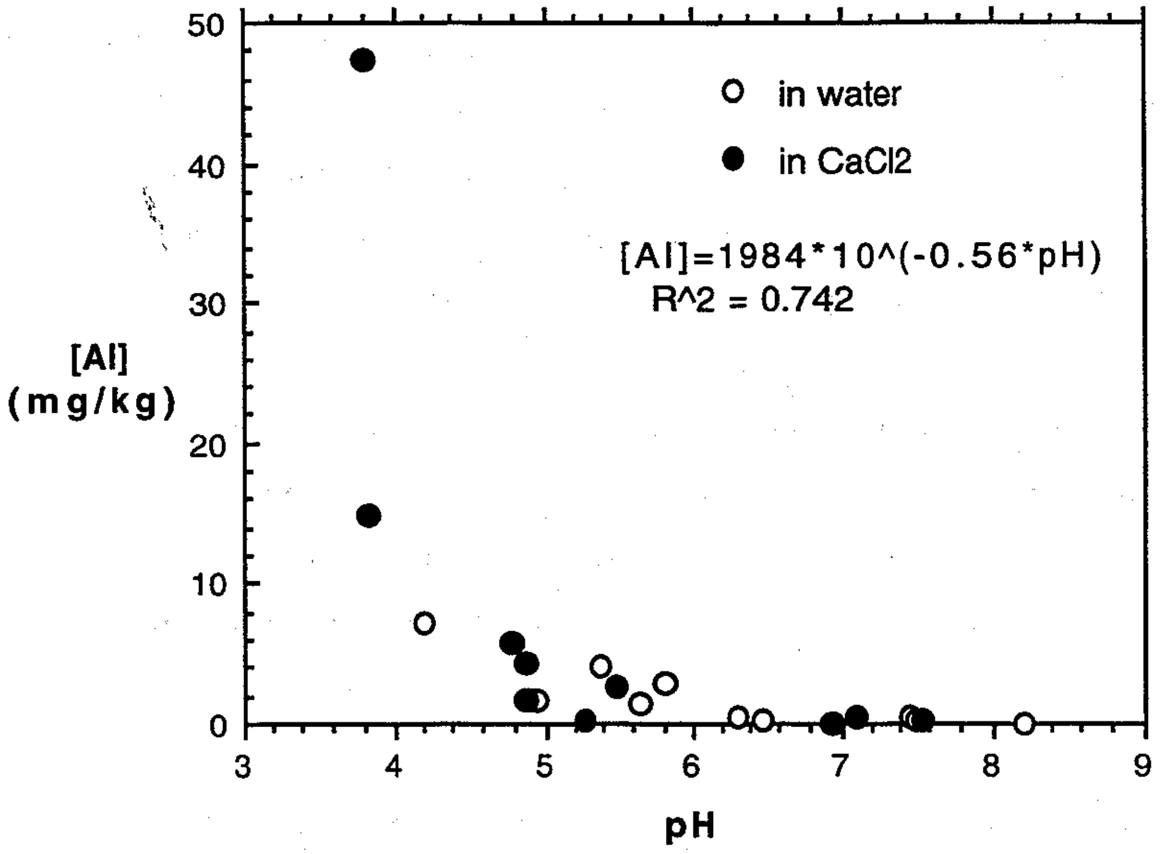

Figure 3. Concentration of aluminium from alum sludge and soils extractable in water or calcium chloride as a function of pH.

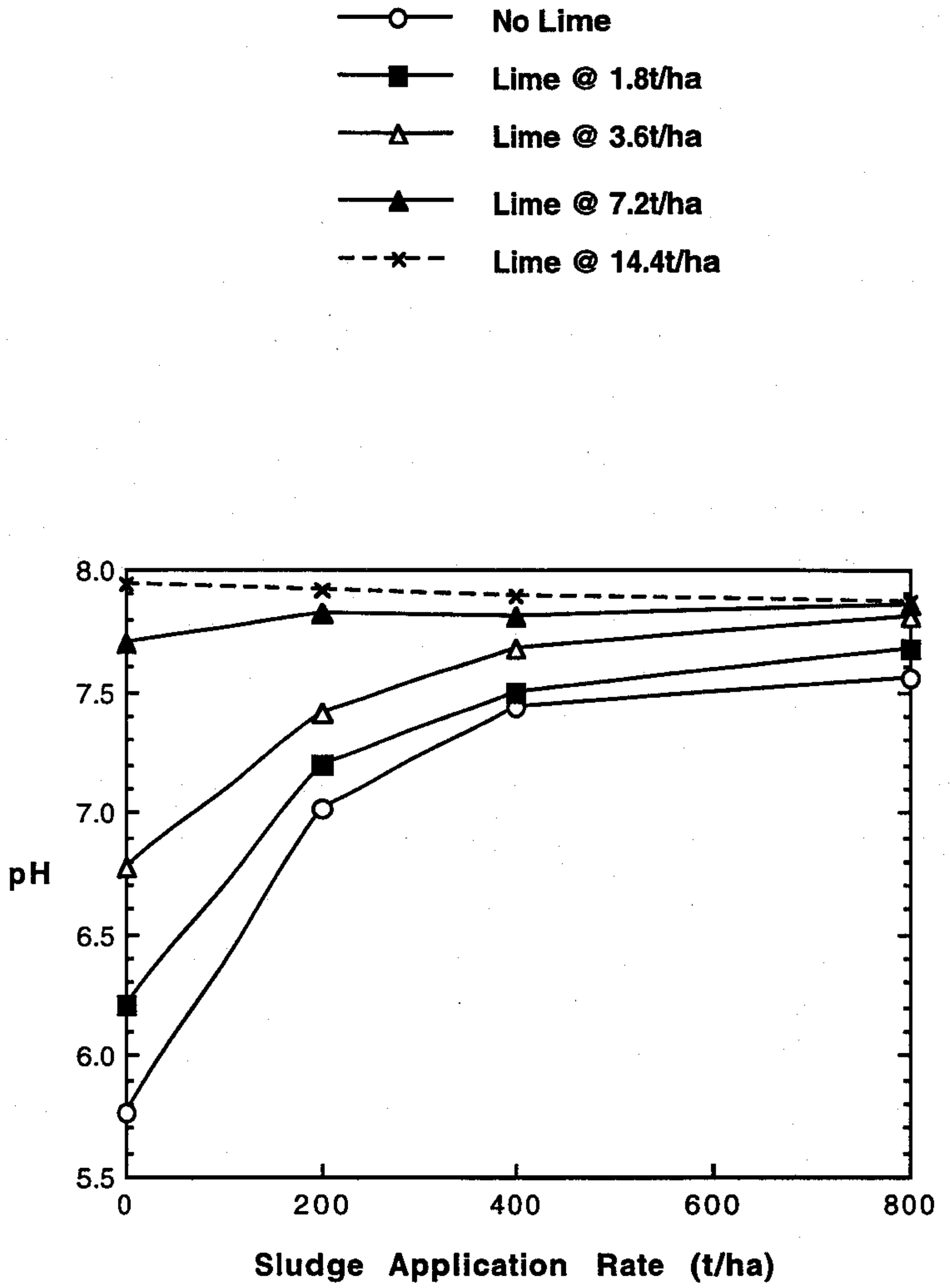

Figure 4. Soil pH in 1:5 soil:water as a function of the application rate of alum sludge or lime ($CaCO_3$), following eight weeks moist incubation.

Addition of 200 tonnes sludge per hectare, for example, increased the soil pH by more than a full pH unit, and had the same effect as adding between 1.8 and 3.6 tonnes $CaCO_3$ per hectare. This result supports the widely practiced (and unregulated) addition of alum sludges as substitutes for lime on agricultural soils in the United States (Che *et al.* 1988).

As would be expected (*cf.* **Figure 4**), the increase in pH caused by the addition of sludge or lime significantly reduced the concentration of aluminium in solution from > 2 mg/kg in the unamended Urrbrae soil down to < 0.5 mg/kg (**Figure 5**). The reduction in aluminium caused by adding sludge alone is compared in **Figure 6** with that caused simply by adding lime, and would not be expected to have any negative or phytotoxic consequences with respect to the environment. In fact, it is clear from this work that the addition of sludge has significant benefits with respect to reducing the concentration of aluminium in solution. This has been confirmed by work done in the United States by Grabarek and Krug (1987), who found land application of alum sludge generated no organic or metal-leachate pollution, nor any plant toxicities with respect to aluminium.

The apparently innocuous nature of alum sludge in the environment may explain why its land application is widely accepted in the United States (particularly in Pennsylvania and Connecticut where it is produced in large quantities), requiring neither local nor state level permits (Grabarek and Krug 1987; Elliot and Dempsey 1991). The work conducted here demonstrates clearly that the presence of aluminium in sludge *per se* is no more harmful than that contained in aluminosilicates, which are ubiquitous in the natural soil environment. The potential phytotoxicity of aluminium is thus related more to the conditions controlling the solubility of aluminium than to the total quantity present in the sludge. Proper management of soil acidity to maintain it at or above approximately pH 6 would be expected to prevent any phytotoxic concentrations of aluminium from occurring, and it seems logical that alum sludges could themselves be used as a substitute for lime in acidic, sandy soils. Furthermore, this work provides no evidence to support concerns (*cf.* Cugley 1994) that aluminium might move into water bodies or have any detrimental effects on aquatic organisms when applied to land in the vicinity of waterways.

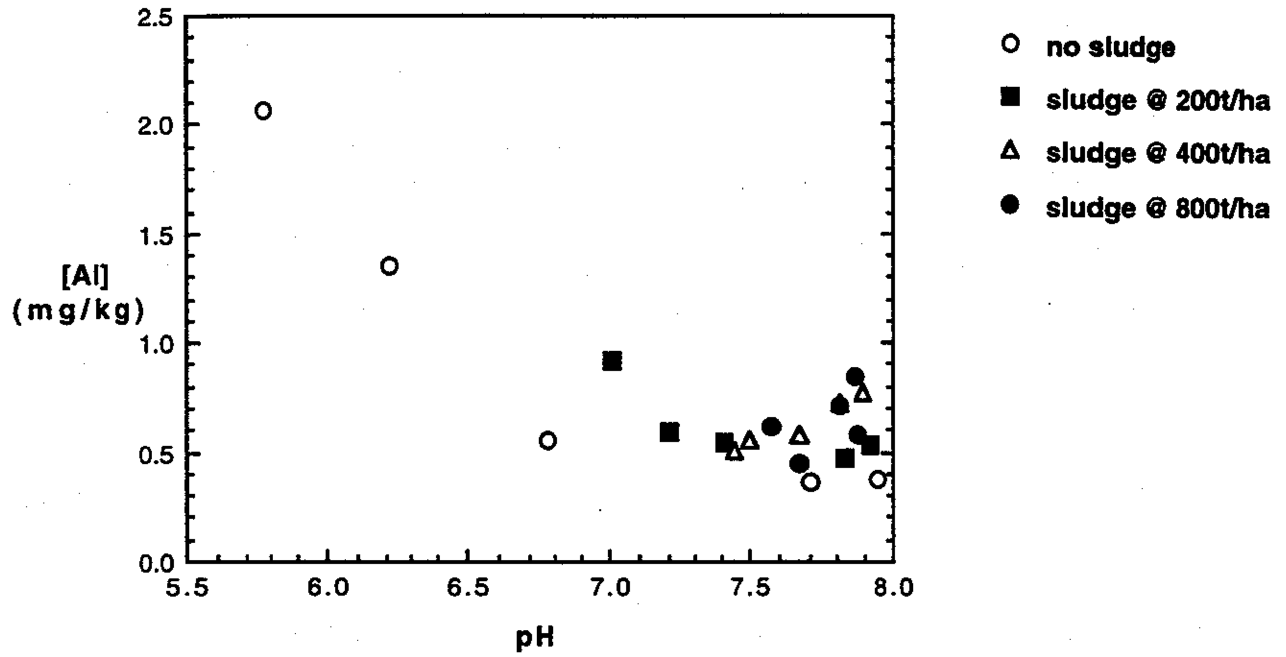

Figure 5. Average concentration of water soluble aluminium in 1:5 soil:water suspensions as a function of pH of suspensions following incubation of soil with alum sludge and lime at different application rates.

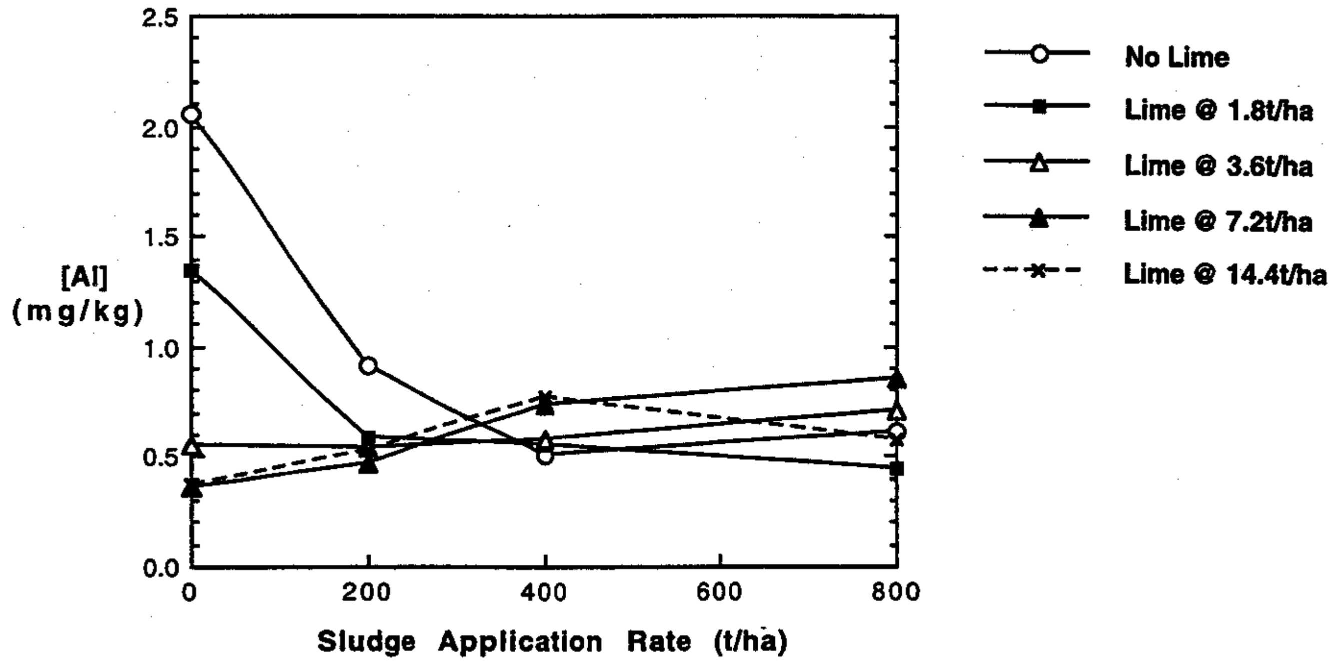

Figure 6. Average concentration of water soluble aluminium in 1:5 soil:water suspensions as a function of the application rate of alum sludge with different amounts of lime added, following moist incubation for eight weeks.

5.3 Effects of alum sludge on performance of lawn grass

5.3.1 Glasshouse study

Visual inspection of the pots indicated that germination of grass seeds depended strongly upon whether the sludge was incorporated or applied only on the soil surface. Incorporation of the sludge allowed satisfactory germination of the seeds at all of the sludge application rates, whereas surface application delayed seed germination, especially with the higher application rates. The germination problem was primarily due to the large aggregate size of the sludge during the early part of the experiment, as this allowed free drainage and poor water holding properties, leading to desiccation of pre-emergent seedlings. This became less significant with time and wetting and drying, because the sludge has a strong self-mulching tendency (*cf* Skene *et al.* 1995) and gradually created a more finely aggregated seedbed, which allowed more even growth and yield (see **Appendix** photos).

Grass dry matter yields for the three harvest periods are shown in **Figure 7a** for pots held at "field capacity" moisture, and in **Figure 7b** for the last two harvest periods when the pots were maintained somewhat drier at 60% field capacity. In general, the yields increased with sludge application rate, and the yields for the surface applied sludge were suppressed only at the first cut (four weeks), after which there appeared to be no significant differences due to method of sludge application (see **Appendix** colour photos). The pots held at field capacity produced somewhat higher yields (**Figure 7a**) than did the pots held at 60% field capacity (**Figure 7b**), which presumably was due to the low content of available water in the sludge (*cf.* **Table 1**) which, when dried much beyond field capacity, may have caused some water stress in the plants.

Similarly, the nitrogen concentration in the grass tissue increased with sludge application rate, and was only suppressed in the surface applied sludge treatment for the first four weeks, shown at 'first cut' in **Figure 8a**. Water status of the sludge-soil mixtures (*ie.* field capacity versus 60% field capacity) had little effect on the nitrogen concentration (**Figure 8b**), which indicates the primary yield increases from the sludge shown in **Figures 7a** and **7b** were due to enhanced nitrogen nutrition. This has also been suggested for work conducted using other sludges supplied at similar application rates (eg. Elliot and Dempsey 1991; Skene *et al.* 1995).

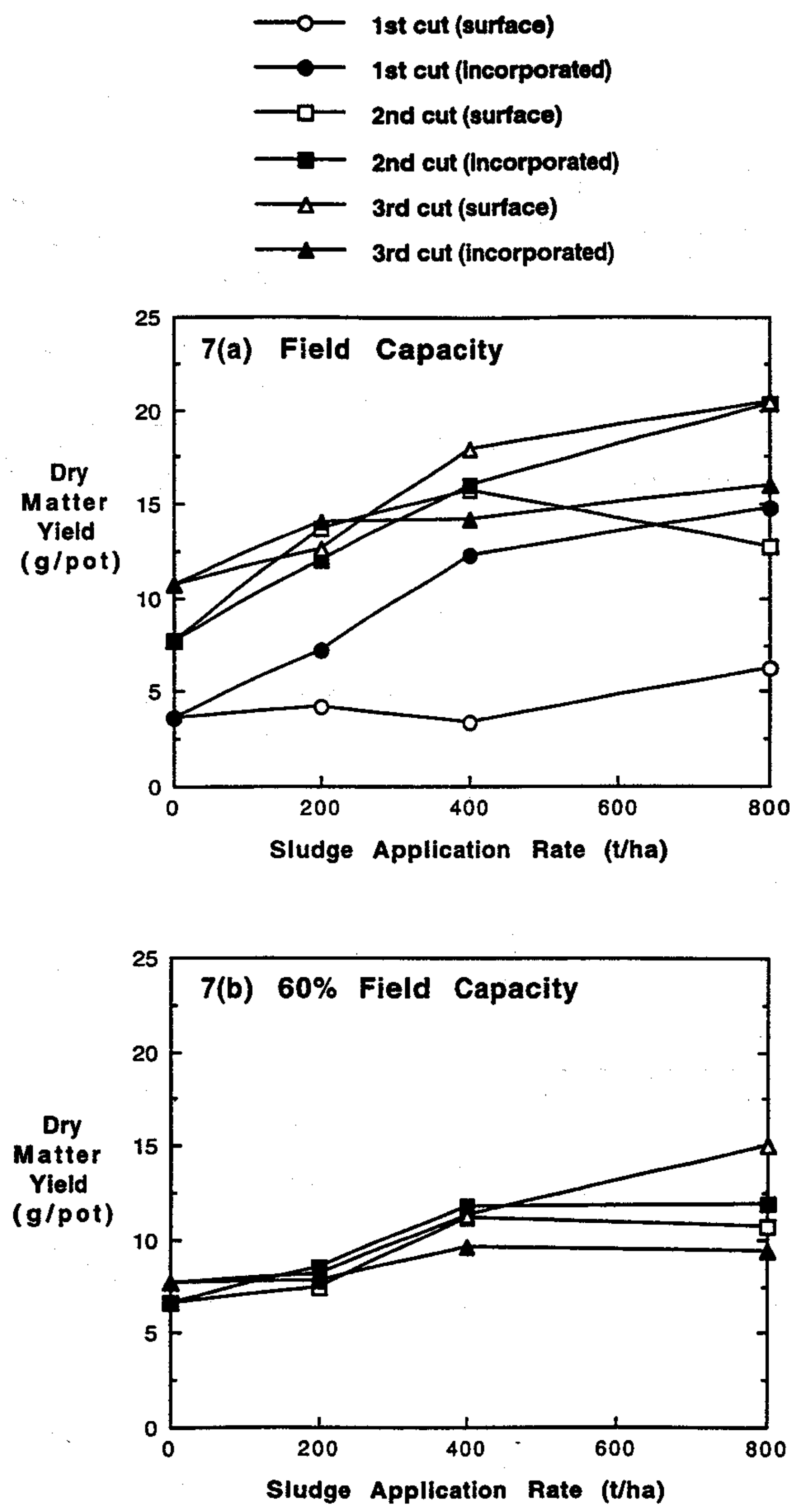

Figure 7. Average dry matter yield of lawn grass in pots as a function of the alum sludge application rate and soil moisture status in pots maintained at (a) 'field capacity' and (b) 60% 'field capacity'.

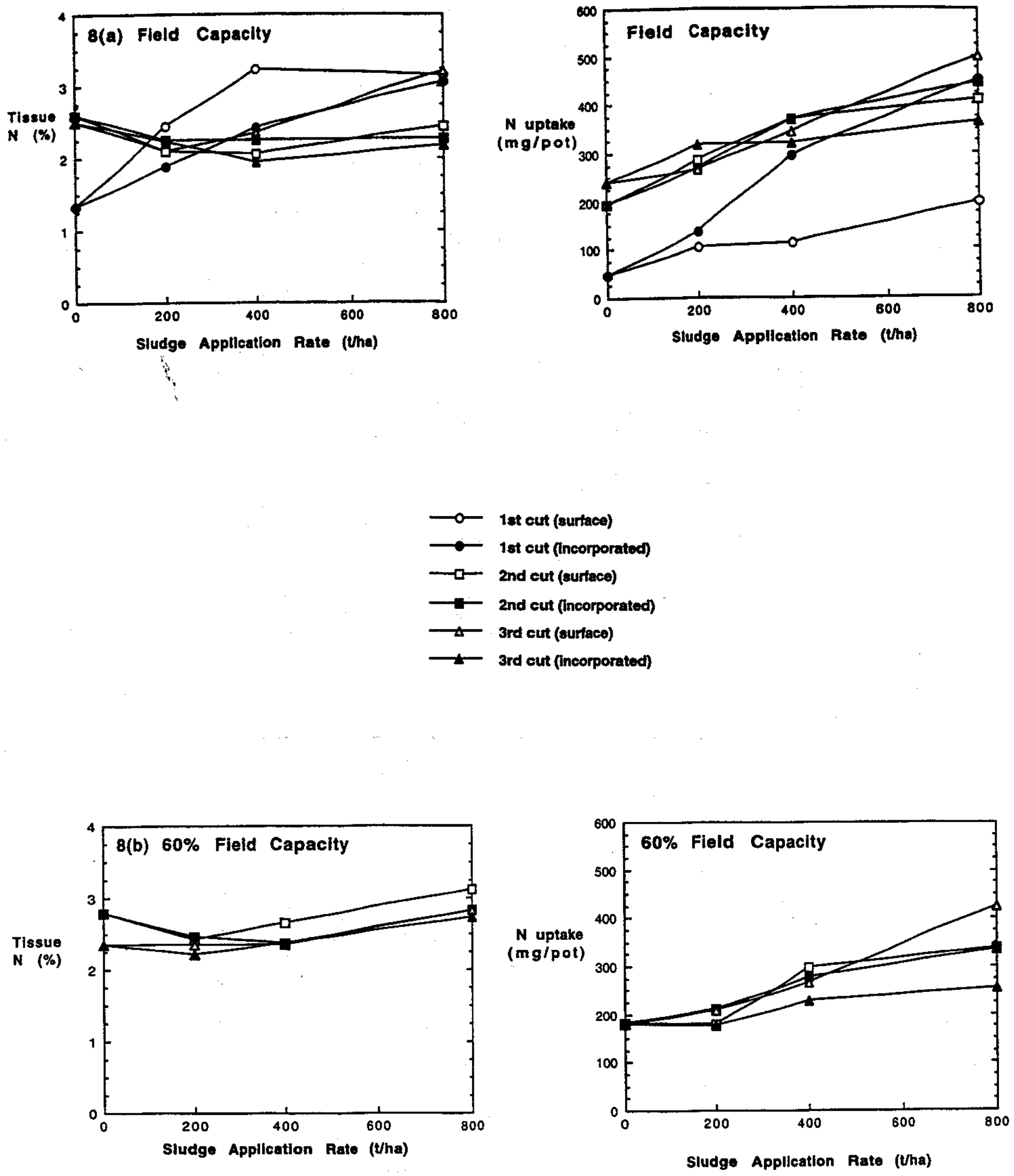

Figure 8. Average concentration of nitrogen in lawn grass tissue, and average nitrogen uptake per pot, as functions of the alum sludge application rate and soil moisture status in pots maintained at (a) 'field capacity' and (b) 60% 'field capacity'.

As might be expected from the high P-fixing capacity of the alum sludge, the P concentration in the grass tissue generally declined as sludge application rate increased (**Figure 9a**) and just as for the nitrogen concentration, the soil water status had little effect in this experiment (**Figure 9b**). There is some suggestion from **Figure 9a**, however, that phosphorus uptake per pot increased with sludge application rates up to 400 t ha^{-1} for the second harvest at 8 weeks and the third harvest at 12 weeks. This indicates the sludge, while having a large P-fixing capacity in the early stages, may have a reasonable P-supplying capacity with time, a phenomenon also noted by Wood *et al.* (1984) in a hardwood forest.

The concentration of aluminium in the plant tissue also decreased with increasing sludge application (**Figure 10a**), and this was also not significantly affected by soil water status (**Figure 10b**). While **Figure 10a** indicates there was a small increase in plant uptake of aluminium with increasing sludge application and harvest time, none of the uptake concentrations were anywhere near the levels that could be injurious to plants (*cf.* Wright 1937). Similarly, the concentrations of Cu and Mn were found to be at optimum levels in the plant tissues, and were not influenced by the rate of sludge application.

5.3.2 Field trial

Visual inspection of the field plots at the Waite Institute revealed that germination of the grass seeds was earlier and more uniform, and greener, in the plots to which only sludge was added (ie. sludge replaced all the soil to a depth of 20 cm - see **Appendix** photos). This is contrary to what happened in the pot experiment, where sludge added at 1600 t ha^{-1} inhibited germination and early growth, but is consistent with the suggestion that over a longer period of time in the field the sludge would "self-mulch" and generate finer aggregates, thus creating a better physical environment for germination and growth of seedlings. Indeed, an examination of samples from all the plots revealed the aggregates of sludge became increasingly finer after wetting and drying over the 14 month experimental period. Furthermore, the addition of increasing amounts of sludge to the soil significantly reduced the dry bulk density and increased the total porosity and infiltration rate.

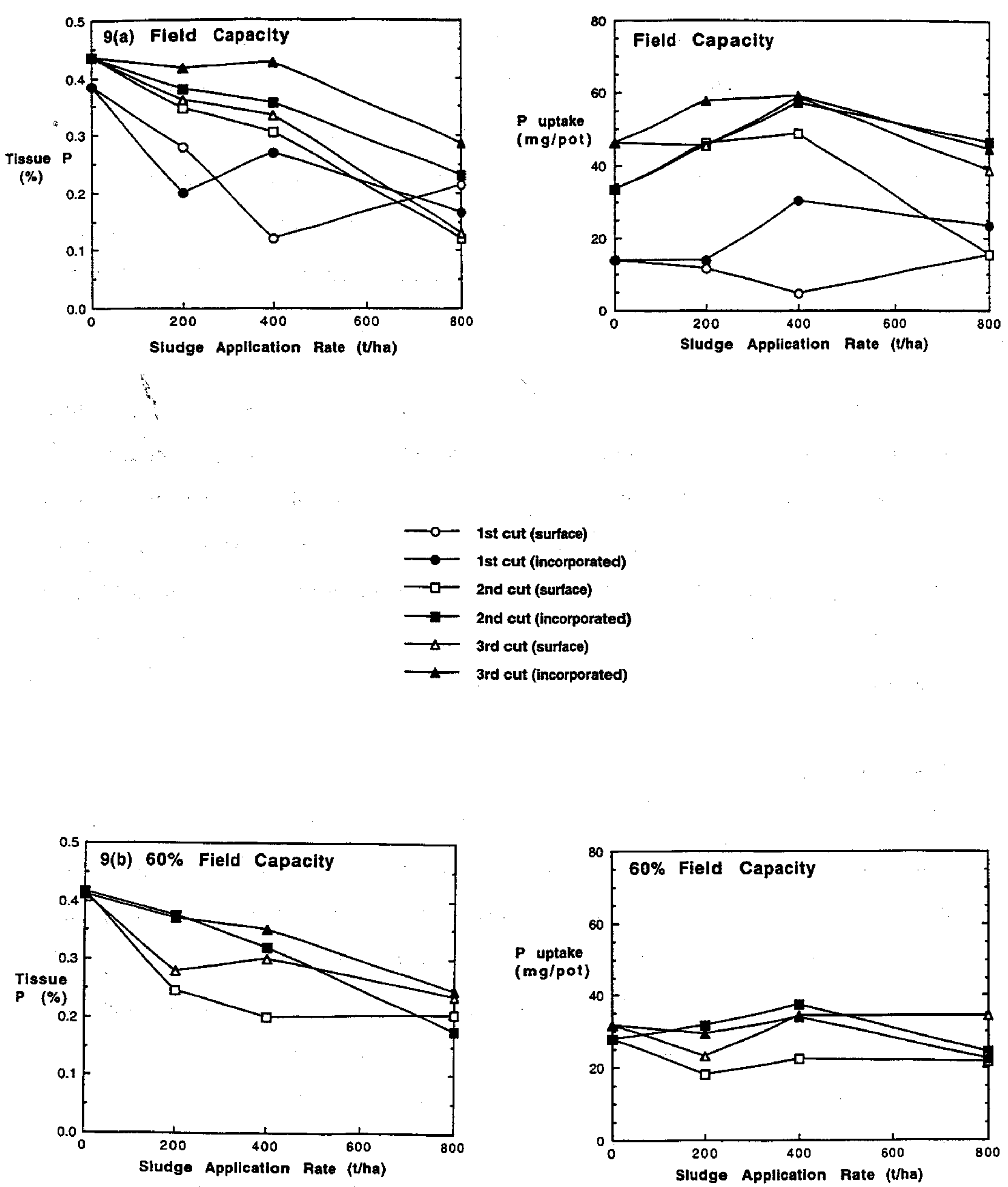

Figure 9. Average concentration of phosphorus in lawn grass tissue, and average phosphorus uptake per pot, as functions of the alum sludge application rate and soil moisture status in pots maintained at (a) 'field capacity' and (b) 60% 'field capacity'.

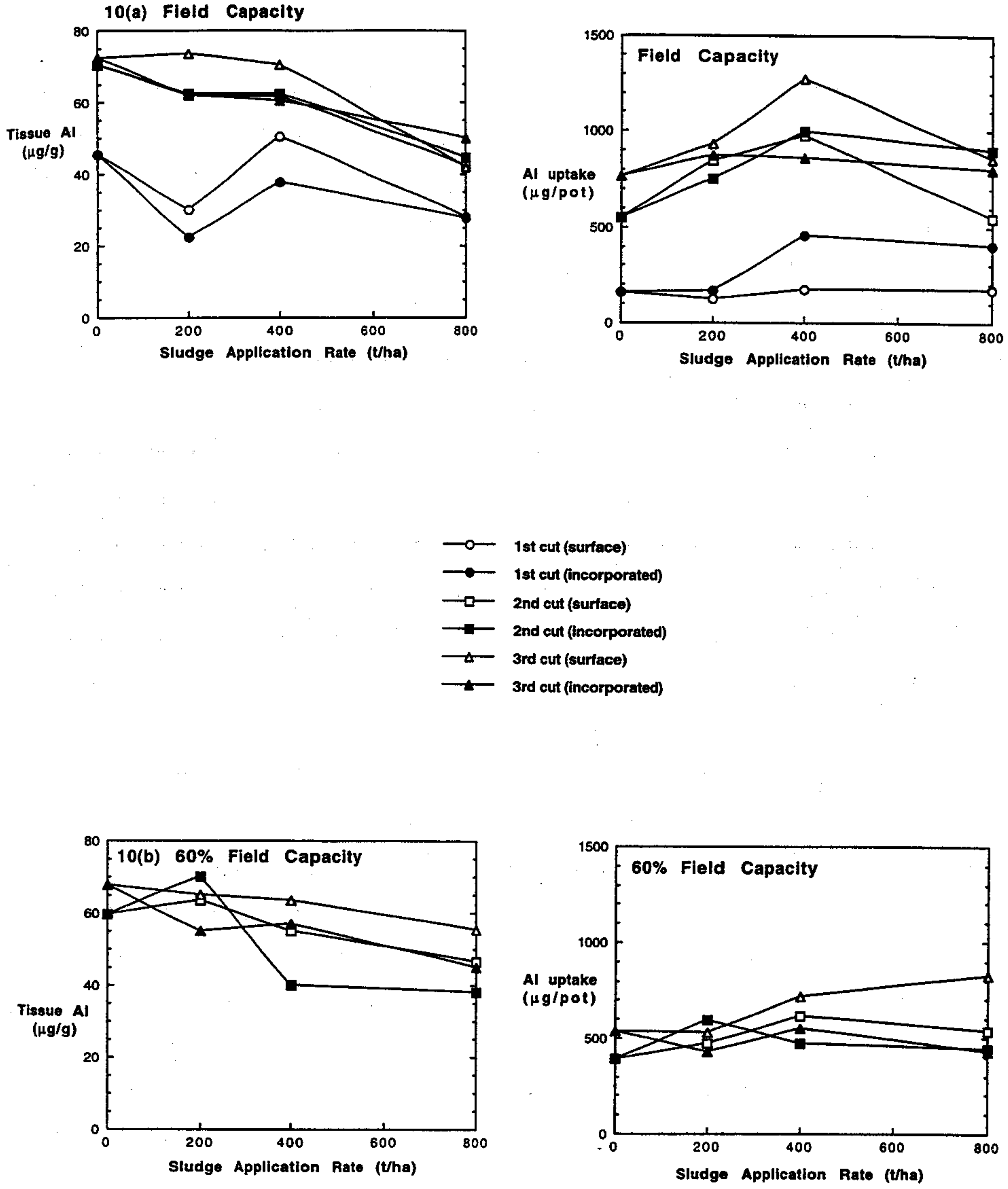

Figure 10. Average concentration of aluminium in lawn grass tissue, and average aluminium uptake per pot, as functions of the alum sludge application rate and soil moisture status in pots maintained at (a) 'field capacity' and (b) 60% 'field capacity'.

The particle density was also reduced by the sludge, but not significantly at P = 0.05 (**Table 4**).

Dry matter yields of lawn grass, the concentration of N in the grass tissue, and the concentration of available N (nitrate) in the soil all increased significantly at the higher sludge application rates only (**Table 5**). Contrary to expectation, the concentration of available P in the soil was not limiting for any of the treatments (**Table 5**), indicating that the P-fixing capacity of the sludge may not be a long-term problem when applied to soils.

5.4 Evaluation of alum sludge as a potting mix ingredient

5.4.1 Properties of the potting mixes

The 34 different potting mixes shown in **Table 5** were found to have air-filled porosity's at field capacity ranging between approximately 12 and 32%, which is largely acceptable under the Australian Standards for Potting Mixes (Australian Standards 1993). On the basis of their water holding capacities, however, only 3 of the 34 mixes were acceptable as "regular grades" according to the Australian Standards criteria; details of these mixes, No.'s 20, 25 and 31, are listed in bold face type in **Table 6**.

By replacing the pine bark with peat moss in these three sludge mixes, the water holding capacity increased to values comparable to the "premium" commercial mixes (**Table 7**), even though this reduced the air-filled porosity somewhat. Importantly, the pHs of all six of the acceptable sludge mixes, whether "regular" (with pine bark) or "premium" (with peat moss) exceeded 6.5. It is usual for potting mixes with either peat moss or pine bark in them to require pH adjustment using dolomite because of the acidic nature of these two organic compounds (Handreck and Black 1994). When combined with the alum sludge, however, this was not necessary, and demonstrates the use of sludge as a practical lime substitute in commercial potting mixes. As shown in **Table 8**, the levels of Cu, Mn, Zn, and B in the mixes containing alum sludge were well within the acceptable limits for both "regular" and "premium" grades of potting mixes, and so no additional fertilisers were necessary for these nutrients. The only essential micro-nutrient that appeared to be limiting in the alum sludge mixes was Fe, and this was corrected by addition of 1 kg m^{-3} ferrous sulfate.

Table 4. Effect of adding alum sludge at different rates in field plots of Urrbrae Red-brown Earth on bulk density, particle density, total porosity, air-filled porosity, and infiltration rate.

Sludge Application Rate (t ha^{-1})	Bulk Density (kg m^{-3})	Particle Density (kg m^{-3})	Total Porosity (%)	Air-filled Porosity (%)	Infiltration Rate (mm h^{-1})
0	1.25	2.56	51	23	398
200	1.21	2.41	50	21	331
400	1.14	2.48	54	24	696
800	1.02	2.44	58	25	1061
1600	0.80	2.36	66	25	1755
LSD	0.09**	NS	3**	NS	454**

** significant at P=0.01; NS = not significant at P=0.05.

Table 5. Effect of adding alum sludge at different rates in field plots of Urrbrae Red-brown Earth on dry matter yield of grass, concentration of nitrogen in grass tissue, concentration of available soil nitrogen (nitrate N), and concentration of available soil phosphorus.

Sludge Application Rate (t ha^{-1})	Dry Matter Yield (t ha^{-1})	N Concentration in Plant (%)	Available N Conc. in Soil (mg NO_3^- kg^{-1})	Available P Conc. in Soil (mg kg^{-1})
0	2.00	1.37	5.2	56.7
200	1.45	1.60	6.2	42.7
400	1.78	1.55	9.5	54.2
800	2.30	1.78	7.7	40.5
1600	3.23	2.01	21.4	38.0
LSD	0.74*	0.37*	6.9**	NS

* = significant at P=0.05; ** = significant at P=0.01; NS = not significant at P=0.05.

Table 6. Composition and physical properties of potting mixes containing alum sludge, pine bark, and coarse sand.

Table 6. Composition and physical properties of potting mixes containing alum sludge, pine bark, and coarse sand.

Mix No.	Composition by Volume (%Bark-%Sludge-%Sand)	Water Holding Capacity (% by Volume)	Air-filled Porosity (% by Volume)
1	50 - 0 - 50	38.7	13.3
2	40 - 10 - 50	36.8	17.8
3	30 - 20 - 50	36.2	11.8
4	20 - 30 - 50	33.9	15.1
5	10 - 40 - 50	30.8	16.5
6	0 - 50 - 50	26.2	17.6
7	0 - 60 - 40	30.4	19.7
8	0 - 70 - 30	24.4	20.3
9	0 - 80 - 20	24.4	28.6
10	0 - 90 - 10	25.1	31.8
11	40 - 20 - 40	34.6	18.6
12	30 - 30 - 40	33.2	19.2
13	20 - 40 - 40	31.4	23.1
14	10 - 50 - 40	27.2	23.0
15	50 - 20 - 30	39.9	22.4
16	40 - 30 - 30	35.3	21.6
17	30 - 40 - 30	39.2	20.7
18	20 - 50 - 30	30.3	24.3
19	10 - 60 - 30	28.0	26.7
20	**50-30-20**	**42.1**	**21.6**
21	40 - 40 - 20	37.0	24.1
22	30 - 50 - 20	36.2	25.0
23	20 - 60 - 20	34.9	25.9
24	10 - 70 - 20	33.3	28.4
25	**50-40-10**	**43.4**	**22.7**
26	40 - 50 - 10	40.6	24.3
27	30 - 60 - 10	41.8	25.2
28	20 - 70 - 10	35.3	26.4
29	10 - 80 - 10	34.2	29.0
30	50 - 50 - 0	43.1	27.0
31	**40-60-0**	**42.3**	**27.2**
32	30 - 70 - 30	39.5	31.1
33	20 - 80 - 0	32.0	29.4
34	10 - 90 - 0	24.9	30.4

Table 7. Water holding capacity and air-filled porosity of the three best potting mixes shown in Table 6, containing either pine bark or peat moss.

Mix No.	Composition by Volume (%Bark or Moss-%Sludge-%Sand)	Water Holding Capacity (% by Volume)	Air-filled Porosity (% by Volume)
20	50 - 30 - 20:		
	Pine Bark (50%)	42.1	21.6
	Peat Moss (50%)	50.9	10.9
25	50 - 40 - 10:		
	Pine Bark (50%)	43.4	22.7
	Peat Moss (50%)	51.4	14.6
31	40 - 60 - 0:		
	Pine Bark (40%)	42.3	27.2
	Peat Moss (40%)	51.7	19.3

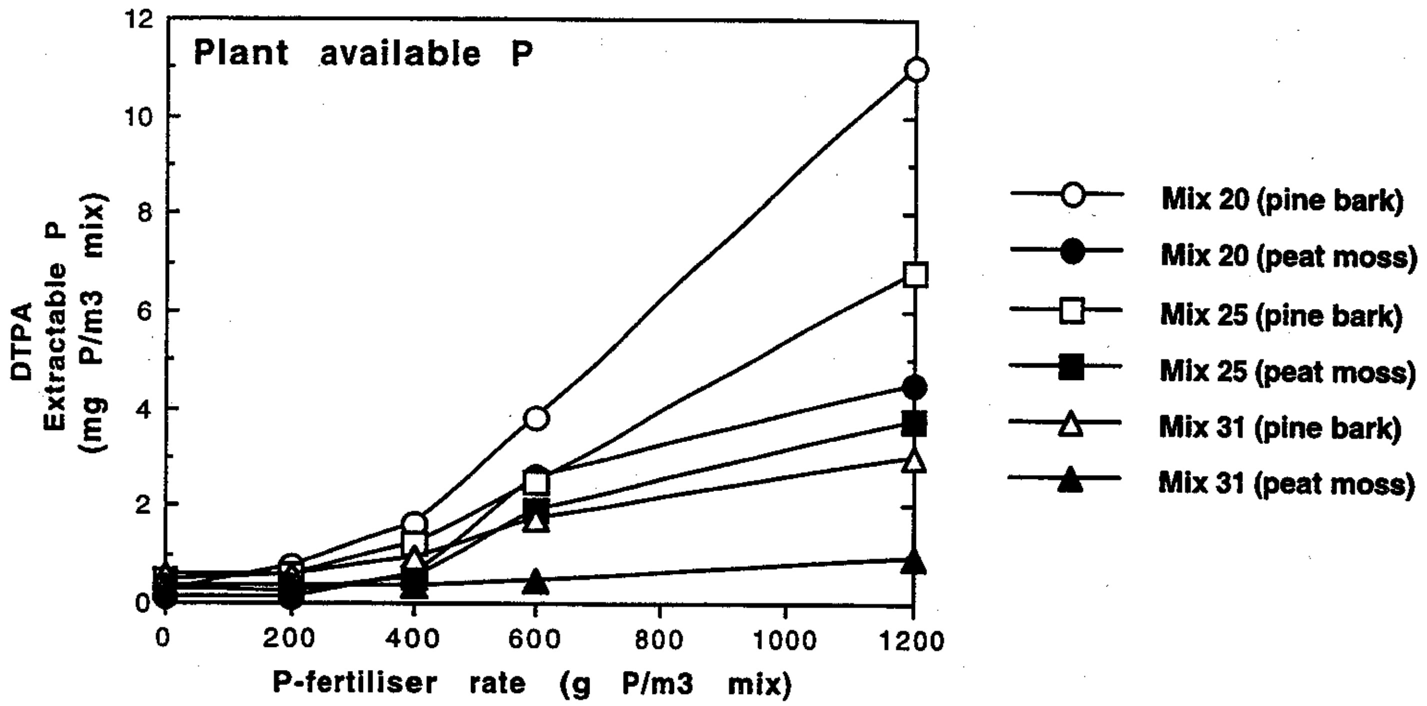

Figure 11. DTPA extractable P (ie. plant available P) as a function of the application rate of P fertiliser to the three 'best ' potting mixes containing alum sludge and either pine bark (regular grade) or peat moss (premium grade).

Table 8. Physical and chemical properties of the potting mixes shown in Table 7, plus two commercially available mixes, without adjustment for nutrients.

Property of Mix	Mix No.20		Mix No.25		Mix No.31		Industry	Standards
	Pine	Peat	Pine	Peat	Pine	Peat	(Regular)	(Premium)
Air-filled pores (%)	22	11	23	15	27	19	> 13	> 13
Wettability (min)	< 2	< 2	< 2	< 2	< 2	< 2	< 5	< 2
Total Water Holding Capacity (%)	42	51	43	51	42	52	> 40	> 50
pH	6.7	6.5	6.9	6.9	7.1	7.1	5.3-6.5	5.3-6.5
EC (dS m^{-1})	0.7	0.6	0.7	0.8	0.8	0.11	< 2.2	< 2.2
Toxicity Index	>90	>90	>90	>90	>90	>90	>75	>75
Nutrient Status								
NH_4^+ (mg l^{-1})	0	0	0	0	0	0	<100	<100
NH_4^++NO_3(mgl^{-1})	11	6	16	2	14	2	n.a.	< 50
N Drawdown Index	0.54	1	0.39	1	0.44	1	>0.2	>0.7
P (mg l^{-1})	0.3	1.5	0.3	2.3	0.4	3	>3	8 - 4
K (mg l^{-1})	51	14	47	14	33	18	n.a.	>50
S (mg l^{-1})	32	9	32	13	30	20	n.a.	>40
Ca (mg l^{-1})	158	113	270	123	279	181	>50	>80
Mg (mg l^{-1})	39	30	42	30	47	39	>15	>15
Ca/Mg ratio	4	4	7	4	6	5	2-10	2-10
K/Mg ratio	1	0.5	1	0.5	1	0.5	n.a	1-7
Na (mg l^{-1})	95	75	105	72	116	99	<100	<100
Cl (mg l^{-1})	142		163		192		<200	<200
Fe (mg l^{-1})	26	10	22	9	16	8	>25	>25
Cu (mg l^{-1})	4	7	5	8	7	12	0.4-15	0.4-15
Zn (mg l^{-1})	1.5	1.4	2	1.9	1.5	1.5	0.3-10	0.3-10
Mn (mg l^{-1})	11	10	12	12	12	16	1-20	1-20
B (mg l^{-1})	tr	0.05	tr	0.05	tr	0.03	0.02-0.65	0.02-0.65

As might be expected, the main limitation to the fertility of the alum sludge mixes was found to be phosphorus. The concentrations of DTPA extractable P as a function of the amount of added P is shown in **Figure 11**, and shows that the mixes with the greatest proportion of alum sludge had the lowest amounts of extractable P. The presence of peat moss in the sludge mixes seemed to reduce the extractable P more than was found with pine bark, and this required amelioration with P-fertiliser at 600 g P m^{-3} to bring the available P up to the desired level.

5.4.2 Growth of marigolds in mixes containing alum sludge

As the data in **Table 9** indicate, the sludge-based mixes produced marigolds with favourably comparable, if not superior, shoot weights and numbers of flowers to the commercially available potting mixes (see **Appendix** colour photos). The sludge-based mixes and the "premium" commercial mixes both performed better than the "regular" mixes, although the "premium" mixes experienced severe Fe deficiencies approximately two weeks after planting, which had to be corrected with Fe-chelate. Of the three sludge-based mixes, the one with the least sludge and the

Table 9. Performance of marigolds in potting mixes containing 30% alum sludge, compared with growth in commercially available potting mixes of regular and premium grades.

Potting Mix Details	Yield of Marigold Shoots (g / plant)	Number of Marigold Flowers per plant
NuErth (Regular Grade)	6.5	3.4
NuErth (Premium Grade)	13.6	6.2
Peat Soil (Regular Grade)	12.3	4.0
Peat Soil (Premium Grade)	15.4	6.0
Mix No.20 (50-30-20):		
Pine Bark (50%)	13.1	7.8
Peat Moss (50%)	17.3	6.8
LSD at P<0.05	2.6	2.9

most sand in it (No.20) had the greatest shoot dry weight (**Figure 12**). This presumably was related to P-fixing problems associated with the mixes with more alum sludge, because (as is plainly visible from the **Appendix** colour photographs) there was a significant growth response (shoot dry weight and number of flowers) to the addition of P-fertiliser (**Figure 13a and 13b**).

6. Conclusions

The work conducted in this project has three main conclusions, summarised as follows:

6.1 There is no evidence in the available literature nor from the studies conducted here to suggest land application of alum sludges poses any environmental or phytotoxic hazard with respect to aluminium pollution. The chemistry of aluminium is controlled largely by pH, and the alum sludges produced by water filtration plants are all treated with lime specifically to raise the pH to the point where soluble aluminium species are minimised. In fact, there is less water soluble aluminium in alum sludge than in many of Australia's commonly occurring acidic soils. If, for example, alum sludge were to be applied to land, even on acidic soils, it would very likely increase the soil pH, and even if the application rates were too low for this, it would be a simple matter to add lime to raise the pH, or to monitor soil pH periodically (as in the agricultural community) and add lime if needed.

6.2 The alum sludge has a number of agronomically beneficial properties, which it imposes on soil to which it is applied. Firstly, there is plenty of nitrogen in the sludge (presumably because of the high content of natural organic matter in the raw water plus the presence of added organic polymers) and this is capable of contributing significantly to the nitrogen requirements of crops. Secondly, it is a highly stable and non-dispersive material which when added to soil reduces its bulk density, increases its porosity and water holding capacity, and also increases its infiltration rate. The improvement in soil physical properties can only aid in plant growth and the rehabilitation of poorly structured soils, particularly those of sandy texture. While the sludge appears to have an enormous P-fixing capacity in the laboratory, the agronomic results of this study suggest that when the sludge is exposed to wetting and drying and ageing, it gradually releases some of its P, and this contributes significantly to the P-nutrition of crops grown in the sludge. If the reverse side of the story is

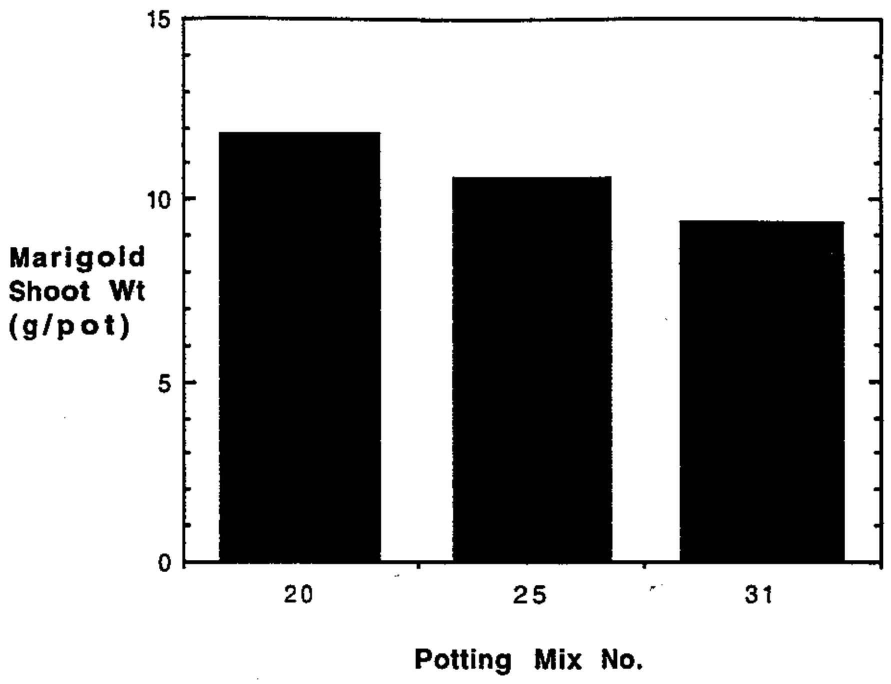

Figure 12. Average marigold shoot weight for the three 'best' potting mixes containing alum sludge.

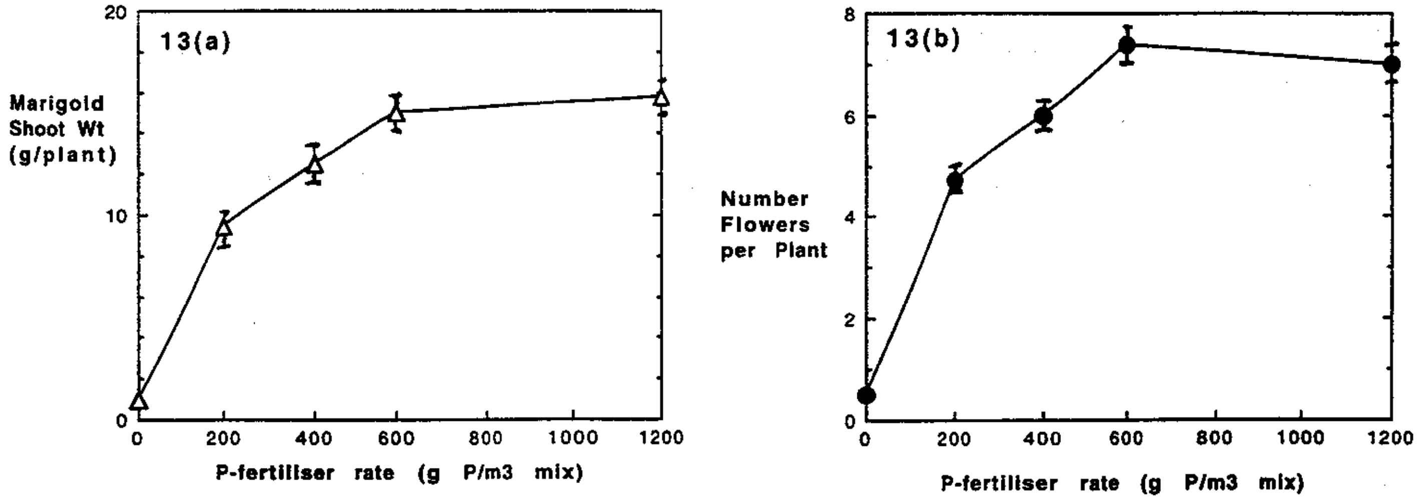

Figure 13. Growth responses of marigolds for the three 'best' potting mixes (composite average) as a function of the application rate of P fertiliser. (a) Average shoot weights, and (b) Average number of flowers per plant.

considered, it is apparent that alum sludge has an enormous potential to sorb P from polluted waters, and once saturated with P might act as slow-release P-fertilizers. The potential for this has yet to be investigated, but is certainly a worthwhile topic of research, considering the many environmental concerns about P in our various sources of freshwater.

6.3 There would appear to be significant potential for alum sludge (and other water treatment sludges) to be used in the potting mix industry. From this investigation, it is clear that where P-nutrition can be managed, the sludge-based mixes compare very favourably with the "regular" and "premium" grades of commercially available potting media for plant growth. The availability of sufficient quantities of sludge to this industry might be the only limiting factor, but from a disposal point of view, this is a considerable advantage.

7. Recommendations

The following recommendations follow from the conclusions of this research:

7.1 Disposing of this valuable resource in municipal landfill sites is unjustified when there are so many possibilities for its practical use and so few disadvantages. So long as the alum sludge has been air dried (thus fixing any soluble aluminium into insoluble oxide and hydroxide forms) it can be released for dispersal without significant regulation at all.

7.2 Because of the limited supply of the sludge, it is best used on moderately acidic, sandy soils and other soils of light texture, as this will raise the pH and improve water holding capacity of the soil, and thus reduce erosion and increase crop productivity.

7.3 There is need for research into the P-sorbing properties of water treatment sludges, and the extent to which this can be managed, in particular to remove P from polluted waters, and also to release it again when applied to land.

7.4 Finally, because there is a negative connotation associated with the word "sludge", its use in reference to water treatment sludges is to be avoided in future; confusion with sewage sludges may then be eliminated. The term water treatment "residue" is a possible alternative which still describes the composition of the material accurately, while also identifying it as being distinct from sewage sludge. Other efforts to increase the public acceptability of this material should also be explored.

Acknowledgments

The authors of this report gratefully acknowledge the financial support of the Urban Water Research Association of Australia, and SA Water (formerly the Engineering and Water Supply Department of South Australia). The opportunity to participate in finding practical solutions to a very real and important environmental problem in Australia has provided considerable personal satisfaction to each of us. We would particularly like to express our thanks to Keith Hayes, Geoff Kilmore and Peter Tarrant (SA Water) for their interest, support and cooperation during the project.

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Dissemination of Results

A. Refereed Publications

i) Ahmed, M., Grant, C.D., Oades, J.M. and Tarrant, P. Concentration of aluminium in alum sludge compared with natural and limed soils: Implications for sludge disposal on land. (to be submitted to *Water*).

ii) Ahmed, M., Grant, C.D., Oades, J.M. and Tarrant, P. Alum sludge and its potential for use in horticulture. (to be submitted to *Comm. Soil Sci. Plant Anal.*).

B. Conference Presentations

i) Ahmed, M., Grant, C.D., Oades, J.M., and Tarrant, P. 1996. Aluminium, soil pH, and the non-phytotoxic disposal of water clarification sludges (residuals) on land. *Aust. and New Zeal. Nat'l Soils Conf*, **2** (oral papers), 3-4. Melbourne. July, 1996.

ii) Macks, S.P. and Grant, C.D. 1996. Physical properties of an alum-flocculated water clarification sludge and their implications for its use as a plant growth medium. *Aust. and New Zeal. Nat'l Soils Conf*, **3** (poster papers), 147-8. Melbourne. July, 1996.

C. Education

Postgraduate Work:
S.P. Macks, Master of Soil Conservation Thesis: "Water treatment sludges and their use in removing phosphorus from contamitated waters" February 1997. Department of Soil Science, The University of Adelaide.

Summer Research Student Work:
Drs C.D. Grant and R.S. Murray won a "Summer Student Award" from the University of Adelaide to supervise the research activities of an undergraduate during a 10 week period in January - March 1997. The student, Ms E. Drew, will be investigating the use of water treatment sludges to reduce the concentration of phosphorus in a number of contaminated water sources in South Australia. It is anticipated this work will contribute significantly to our understanding of some of the practicalities associated with using sludges in this manner.

***Overseas Interest in the Work*::**
An Italian undergraduate student, Mr Max Trenta, has expressed interest in the sludge work and is competing for an "Australian-European Awards Program Postgraduate Scholarship" to come here in 1998 to conduct research using water treatment sludges.

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(referred to in text)

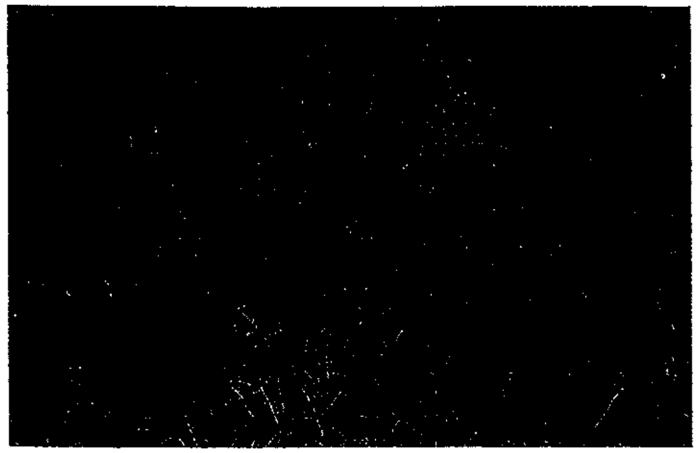
Moist alum sludge from Happy Valley Water Treatment Plant delivered to Waite Institute.

Range in aggregate size of sludge before (right) and after (left) wetting and drying.

Sludge mixed with soil at various application rates prior to placing into field plots.

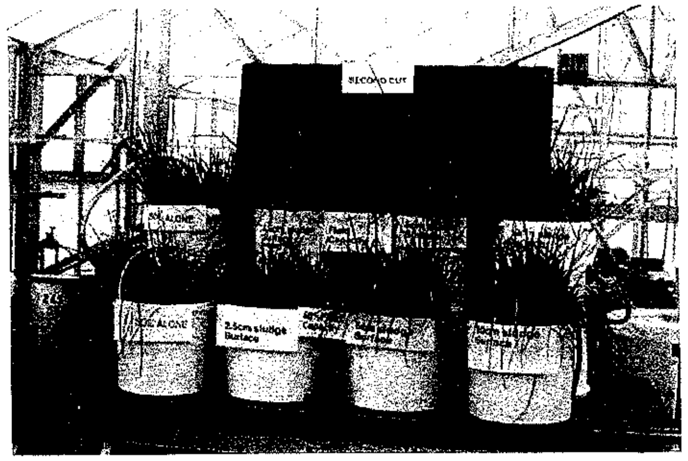
Field plots bounded by planks; piles of sludge (left) and soil (right) shown in background.

Plots being filled in with sludge/soil mixes, contained by planks of wood.



Greener, lusher growth of long grass shown on all-sludge plot compared with no-sludge plot.

Lawn grass growing in glasshouse pots of sludge/soil mixtures, illustrating early problems with seedling establishment when coarsely aggregated sludge alone is used, or if coarse sludge is applied to the soil surface instead of incorporating it into the soil.



Pots of lawn grass prior to second cut, showing effects of surface application vs incorporation, and showing effect of drainage to 'field capacity' or 60% 'field capacity'.

Marigolds grown in the best sludge-based mix compared with two commercially available potting mixes, Nu Erth and Peat Soil (premium and regular grades).

Phosphorus response of marigolds in sludge-based potting mixes, showing superior nature of the pine bark (left) as compared with the peat moss (right) in the mixes (*cf* Figure 11 plant available P for Mix 20-pine bark compared with Mix 31-peat moss).

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