University of Alberta

Soil and Plant Response to the Field Application of Fly Ash

by

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A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

Reclamation

Department of Soil Science and Department of Plant Science

Edmonton, Alberta

Fall, 1995

ISBN 0-612-06477-8

University of Alberta

Library Release Form

Name of Author: Andrew Markus Hammermeister

Title of Thesis: Soil and Plant Response to the Field Application of Fly Ash

Degree: Master of Science

Year This Degree Granted: 1995

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Everyone has a right to their opinion,

but no one has a right to be wrong in their facts.

Bernard M. Baruch

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Soil and Plant Response to the Field Application of Fly Ash" submitted by Andrew Markus Hammermeister in partial fulfillment of the requirements for the degree of Master of Science in Reclamation.

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DEDICATION

I would like to dedicate this thesis to my parents who have supported and encouraged me throughout the development of my career and in all that I do.

To:

Harold and Gisela Hammermeister

ABSTRACT

Field application of fly ash, a by-product of coal combustion, as a soil amendment provides the dual benefit of alleviating waste management concerns and potentially improving the soil for plant growth. However, fly ash may adversely influence some ecosystem components. In this field study we measured fly ash influence on trace element accumulation, growth, and development of selected plant species, and on temperature of amended soils. Boron concentration in plant tissue increased with fly ash rate to toxic levels. The copper:molybdenum ratio of vegetation decreased with increased fly ash rate to levels severely deficient for livestock at upper rates of application. Mean daily soil temperature was lower on fly ash amended plots but was likely of little biological significance. Potential yield benefit at intermediate fly ash rates and decrease at high rates was observed but not statistically significant. Further research is required to quantify yield benefit of fly ash amendment on problem soils in western Alberta.

ACKNOWLEDGEMENTS

Many people, with their wisdom and support, have inspired creative thought of which I never realized I was capable. In this regard I thank my supervisors, Dr. Anne Naeth and Dr. David Chanasyk for their confidence in my abilities, motivational attitudes, and inspiring discussions. Greatly appreciated financial support was provided by TransAlta Utilities Corporation, a Province of Alberta Graduate Scholarship, Canadian Land Reclamation Association Scholarships, an Alberta Sugar Company Scholarship, and a MacAllister Scholarship in Agriculture. Technical support was provided by Kelly Ostermann, Robin Lagroix-Maclean, Chung Nguyen, and John Konwicki. The Friends of the Pedon provided much needed recreation, irrelevant discussion, and amusing anecdotes which I will never forget. I would especially like to thank my wife, Desirée, for providing foundation, foresight, and focus to my life; Harold, Gisela, Jason, Edgar, Marilyn, and Logan Hammermeister for helping me keep a family focus in my life; and my mother-in-law Anita Jans for all her support. I would also like to thank Dr. Darwin Anderson for his guidance, Lorne Letkeman for his faith and kind heart, and Dr. Fred Bentley for his mentorship.

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1. INTRODUCTION: JUSTIFICATION OF THESIS RESEARCH

1.1 BACKGROUND

In this period of global concern over effects of human activities on environmental sustainability, industries are beginning to face great pressure from society to maximize the use of non-renewable resources and to improve waste management practices. Occasionally an industrial by-product is found to have useful applications. This not only relieves disposal problems but also provides some benefit to society. When applied as a soil amendment, one such potentially useful substance is fly ash, a 'waste' by-product of coal fired electrical generating stations.

The physical, chemical, and mineralogical properties of fly ash and the ecological and agronomic consequences of its application as a soil amendment have been reviewed by several authors (Carlson and Adriano, 1993; Sharma et al., 1989; El-Mogazi et al., 1988; Ziemkiewicz et al., 1981; and Adriano et al., 1980). Fly ash is defined as the portion of ash produced in coal combustion that has a sufficiently small particle size to be carried away from the boiler in flue gas (El-Mogazi et al., 1988). The process of formation and mineralogical, physical, and chemical properties of Alberta fly ash is briefly described by Joshi (1981). The effect of fly ash on soil is dependent on the physico-chemical properties of the ash. These properties are in turn dependent on the parent coal, operating conditions at the power station, method of collection including forms of pollution control and collection additives, and method of disposal. Thus fly ash composition varies among power stations (Joshi, 1981; Sharma et al., 1989; Carlson and Adriano, 1993). The properties of fly ash also vary by degree of weathering. Fresh (unweathered) fly ash has not been exposed to soil weathering processes and is characterized by high concentrations of soluble salts. Thus, weathered fly ash has been exposed to soil weathering processes and/or has been leached during disposal as is the case for lagooned ash. Weathered fly ash typically has a lower soluble salt content than fresh fly ash.

On average, combustion of sub-bituminous coal produces 15% ash by weight, of which 70 to 80% is fly ash and the remaining 20 to 30 % is bottom ash (Joshi, 1981). Bottom ash is defined as the portion of ash produced from coal combustion which remains in the boiler. Over 2.2 million tonnes of fly ash are produced annually in the coal fired power stations of TransAlta Utilities Corporation in Alberta. Approximately 10 to 20% of fly ash is used as an additive in cement and concrete and in engineering functions such as road construction and as a fill material (Watson, 1994; Joshi, 1981). The remainder is disposed of in lagoons, pits, or stockpiles (Carlson and Adriano, 1993). From field and greenhouse research, several authors have suggested that many chemical constituents of fly ash may benefit plant growth by improving the agronomic properties of problem soils (Carlson and Adriano, 1993; Adriano et al., 1980). However, potentially high concentrations of some trace elements in fly ash may pose a danger to ecosystems.

Numerous studies of fly ash have already been extensively conducted at the University of Alberta. Pluth et al. (1979) characterized several western Canadian fly ashes, assessed its potential as a liming agent, and conducted a greenhouse investigation of Se uptake in barley. Fly ash mineralogy, weathering, and leachability of elements was extensively studied by M.J. Dudas and C.J. Warren (Dudas and Warren, 1988; Warren and Dudas, 1984; Dudas, 1981). In his M.Sc. thesis, Lussier (1994) evaluated the influence of fly ash on soil tilth parameters. Watson (1994) studied fly ash influence on soil texture and determined subsequent implications to soil water holding capacity and modulus of rupture. Most recently, Salé (1995) studied the influence of fly ash on soil crusting and on trace element uptake, yield, and development of barley in a greenhouse.

1.2 FLY ASH INFLUENCE ON SOIL AND VEGETATION

The potential and observed effects of fly ash amendment on soil properties (Table 1-1) and on terrestrial ecosystem processes (Table 1-2) have recently been summarized by Carlson and Adriano (1993). Overall, the influence of fly ash on soil is dependent upon the nature and quantity of fly ash applied and properties of the unamended soil; particle size analysis and pH are of particular importance. Potential benefits include improved water holding capacity, plant available water, water infiltration, aeration, and soil pH, soil warming, increased colloid generation, increased plant growth, and reduced soil crusting (Carlson and Adriano, 1993). Potential limitations of fly ash amendment on soil include deficiency of some nutrients (N, P, and possibly Cu, Mn, Zn), phytotoxicity of some elements (B and possibly As) and food chain concerns related to bioaccumulation (Mo and Se). Fly ash may also lower organic matter content, increase salinity and toxic salt concentration, increase erosion susceptibility, decrease microbial activity, cause cementation of the soil, and reduce cation exchange capacity (Carlson and Adriano, 1993) Ziemkiewicz et al. (1981) noted that soil trafficability may also be reduced with fly ash amendment.

Most authors have indicated that B toxicity is the greatest limiting factor to fly ash utilization as a soil amendment (Carlson and Adriano, 1993; Sharma et al., 1989; El-Mogazi et al., 1988). Reasonably accurate maximum application rate guidelines could be established if variability in B concentration in fly ash was minimal. However, total B concentration ranges from 10 to 600 ug/g among power stations in the United States (El-Mogazi et al., 1988). Total B concentration can also vary with time from a given power station as operating conditions are adjusted and different coal seams or parts thereof are mined. Total B concentration of Sundance fly ash ranged from 5 to 309 ug/g from thirteen sample dates over an eleven year period (TransAlta Utilities Corporation, unpublished analysis data, 1981-1992). Long term variability in fly ash chemistry (months to years) is expected to be greater than short term variability (weeks to months) (McCoy et al., 1981). Due to the variability in fly ash chemistry, standard rate recommendations are difficult to develop and comparisons among research studies are confounded. The utilization of weathered instead of unweathered fly ash would reduce B phytotoxicity and salinity problems, while retaining most benefits of application and permit higher application rates (Carlson and Adriano, 1993).

The liming potential of fly ash is regarded as one of the primary potential benefits of fly ash application. For pH adjustment, the neutralizing potential of fly ash is at best 20 to 25% as effective as $CaCO_3$ (Carlson and Adriano, 1993; Pluth et al., 1981). Unfortunately, application of the required quantity of fly ash to bring soil to a desired pH could raise B concentration to levels toxic to plants (Pluth et al., 1981). Due to a high CaO concentration, fly ash may also be used to decrease an unfavorable sodium adsorption ratio of some problem soils (Pluth et al., 1981; Lutwick et al., 1981).

In a greenhouse experiment, Lutwick et al. (1981) measured barley and alfalfa yield when fly ash was mixed with acidic, saline, and saline sodic mine spoils, changes in chemical composition of plants grown on various ash-soil mixtures, and subsequent changes in their chemical and physical properties. The maximum rate of fly ash application was 10% (w/w). On the acidic Solonetz soil, electrical conductivity, pH, and hydraulic conductivity increased and SAR decreased. Despite these improvements, no yield increase resulted from fly ash addition to the acidic Solonetz soil. On saline sodic mine spoil, modulus of rupture decreased with ash addition. B toxicity was observed in barley for all fly ash treatments. Yield of barley and alfalfa on the alkaline Solonetz decreased with all rates of fly ash application. From this study, Lutwick et al. (1981) suggested that fly ash has greater potential to amend the physical and chemical properties of acidic soils than of alkaline soils, and that higher rates of ash application were probably needed to significantly improve the physical properties of sodic soils. They speculated that with adequate drainage, the problems of increased salts and B availability should be temporary.

From field and greenhouse bottom ash reclamation studies, Natsukoshi (1981) found that greenhouse research could yield results contradictory to those from field research. She measured a yield increase and improvement plant quality in the field but opposite trends in the greenhouse. Natsukoshi suggested that this discrepancy was related to masking of some benefits of fly ash application under the controlled greenhouse conditions. B toxicity may also be more severe in a greenhouse study since plant roots and leachable B are contained within a 'closed system'.

1.3 ASSESSING FLY ASH SUITABILITY AS AN AMENDMENT AND RESEARCH NEEDS IN ALBERTA

Discussion groups at a workshop on coal ash and reclamation in Alberta provided some useful insights regarding the application of coal ash (both bottom and fly ash) as a soil amendment (Ziemkiewicz, 1981). The conclusions from these group discussions are summarized as follows:

- Four situations were identified where ash could be applied:

  a) orphaned land - where there is an absence of topsoil or non-sodic material available, there is a possibility of using a bottom ash cap over unsuitable subsoil. Fly ash could also be applied and/or incorporated by deep ripping to improve penetration of water and roots;

  b) soil reconstruction - where there is a shortage of suitable topsoil material, (e.g. a thin solonetzic Ah horizon), it may be improved by using bottom ash to contribute Ca and lower bulk density thereby 'stretching' available topsoil material;

  c) subcapping - i) where there is a shortage of buffering material between the sodic spoil and replaced topsoil, and, ii) where bottom ash could enhance water holding capacity and/or extend root zone of an unfavorable subsoil;

  d) as a lime substitute on acid soils.

- For improving the physical properties of dense clayey soil or spoil, bottom ash was favoured over fly ash due to its coarser particle size and fewer chemical problems.
- Utilization of fly ash on sodic material would provide little benefit due to its already high pH.
- Application of fly ash on acidic materials, including Luvisolic and Solonetzic soils, may improve soil chemical properties although utilization of ash is not as effective as conventional liming agents and is accompanied by problems such as B phytotoxicity.
- The possibility of fly ash causing Cu deficiency in livestock feeds was recognized.
- Trafficability and erosion become serious problems as fly ash rate increases.
- Optimum application rates need to be determined.
- Improved methods of application and incorporation must be developed including incorporation into problem subsoil.
- Utilization of ash in reclaiming orphaned spoil areas and on undisturbed sites needs further research.

- Agronomic species which are effective in removing toxic substances from fly ash need to be identified.
- Results from greenhouse studies may not represent actual response from field application of fly ash.
- The Sundance power station was forced to change from lagoon to dry haul disposal of fly ash due to proximity of the former lagoon to Wabamun Lake. Relocation of the lagoon was not feasible due to cost. As a result, weathered fly ash is no longer available from the Sundance power station.

1.4 JUSTIFICATION FOR FURTHER RESEARCH AND THE NATURE OF THIS STUDY

Despite extensive research in Alberta and around the world, the suitability of fly ash as a soil amendment has not been adequately determined. In Alberta, no other suitable form of utilization has been accepted widely enough to relieve waste management concerns. The absence of a conclusion regarding ash utilization as a soil amendment is primarily due to the variability in ash chemistry among coal sources and power stations. Given a constant ash chemistry, the result of application could vary if different soil types and plant species were used in assessment. To be an effective soil amendment, fly ash must provide an economically significant crop yield benefit without producing any threat to ecosystem function or its components including soil, air, vegetation, and water or as sources of human and animal nutrition.

Fly ash was used in this study instead of bottom ash since it accounts for 70 to 80% of total coal ash production in Alberta and is therefore considered a priority from a waste management perspective. The workshop group discussion sessions described above also identified the need for further fly ash research on undisturbed sites.

Since the Sundance power station is a primary producer of fly ash, and weathering of the ash by depositing it in lagoons or by some other technique is not feasible, fresh fly ash from the Sundance power station was used. In addition, fresh fly ash represents a worst case scenario.

A field study was conducted instead of a greenhouse study so crops could be grown in conditions where all of the interacting components of the environment contribute to determination of plant response to fly ash. Field research is also a closer representation of the management practices which would be employed in large scale utilization of fly ash as a soil amendment.

The study was located on reclaimed land at the Highvale coal mine to eliminate potential liability problems for TransAlta Utilities Corporation, and due to a lack of suitable undisturbed sites on mine property. The selected reclaimed land was a reasonable substitute for undisturbed agricultural lands since topsoil and subsoil materials had been spread over the spoil materials.

Based on previous research in Alberta, the potential benefits of soil physical improvements from an ash amendment are as great as chemical benefits. However, the risks from fly ash application are predominantly related to chemical alterations in soil and vegetation.

In most studies, fly ash application rates did not exceeded 10% fly ash, however, in some studies, rates as high as 30% fly ash have been applied. To amend unfavorable soil physical properties, higher fly ash rates may be required. During field application of fly ash, overlaps and/or spills may result in adverse effects from excessive applications on such places. Previous authors have indicated that optimum rates of fly ash application are typically in the range of 100-150 t/ha. Considering these recommendations and concerns, the following fly ash treatments were employed: 0, 25, 50, 100, 200, and 400 t/ha. The 400 t/ha treatment equates to approximately 36% fly ash in the top 10 cm of amended soil (note: assuming soil bulk density of 1.1 Mg/m^3).

Barley, alfalfa, and brome grass were used in this study because they are the common cereal and forage species used in the region surrounding the Highvale coal mine.

Few researchers have considered the influence that fly ash may have on soil temperature and no reports of systematic measurements were found. Some researchers have speculated that temperature of a fly ash amended soil will be higher than the same unamended soil. The growing season in the Highvale mine region is short relative to other parts of the province. Earlier soil warming in spring could be an additional benefit of fly ash application. However, considering that fly ash in Alberta generally has a light-grey to light-cream color (Joshi, 1981), one would expect increased reflectance of radiation from the soil and thus a cooling effect. To investigate this hypothesis, we monitored soil temperature of selected fly ash amended plots at 5-, 10-, and 20-cm depths.

1.5 OBJECTIVES

The objectives of this research were to determine the nature and extent of influence of field application of fly ash on:

1. Selected chemical properties of reclaimed soil;
2. Growth, development, and chemical composition of barley, alfalfa, and brome;
3. Nutritional value of feed for livestock;
4. Soil temperature;

From these measurements, acceptable fly ash application rates would be identified.

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Table 1-1. Potential and observed effects of fly ash amendment on soil properties (Carlson and Adriano, 1993)

Soil property	Typical agricultural soil	Soil amended with weathered ash	Soil amended with unweathered ash
aeration	high	higher	higher
bulk density	1.3 (avg.)	lower	lower
cation exchange capacity	medium to high	lower	lower
cementation	low	low	may be increased by addition of alkaline ash
electrical conductivity	low	moderate to higher	higher
hydraulic conductivity	high	increased by low rates; decreased by high rates	increased by low rates; decreased by high rates
microbial activity/diversity	high	may be increased or decreased by low rates; decreased by high rates	may be increased or decreased by low rates; decreased by high rates
modulus of rupture	high	lower	lower
nutrient availability	balanced supply of nutrients	deficient in N, P, and potentially Cu, Mn, Zn, potential phytotoxicity of B and food chain concern with Mo and Se	deficient in N, P, and potentially Cu, Mn, Zn; potential phytotoxicity of B and food chain concern with Mo and Se
nutrient content	all nutrients present	very low N; may have elevated B; others present	very low N; often have excess B; others present
organic matter	high	lower	lower
pH	6.0-7.5	<6.0 to ≅ 8.0	<6.0 to ≅ 12.0
plant-available water	high	no effect to large increase, depending on soil type and rainfall amount	no effect to large increase, depending on soil type and rainfall amount
salinity	low	moderate	high but diminished after 2-3 yr
temperature	adequate	higher	higher
toxic salts	none	may have enough B to be toxic to sensitive plants	high B and soluble salts of Ca, K, Mg, Na
water erosion	resistant	more susceptible	more susceptible
water holding capacity	high	higher	higher
wind erosion	resistant	more susceptible	more susceptible

Table 1-2. Potential effects of soil amendment with fly ash on terrestrial ecosystem processes (Carlson and Adriano, 1993).

	Impact of soil amendment at rates of:		
Process	< 100 t/ha ash	100 to 400 t/ha ash	> 400 t/ha ash
N mineral-ization	generally no effect; may decrease in low-o.m. soils	generally no effect; may decrease in low-O.M. soils	may decrease
nitrification	no effect to some decrease	generally decreased	decreased
denitri-fication	increased	no effect	may decrease
microbial respiration	no effect to slightly reduced	reduced	greatly reduced to totally inhibited
soil alkalinization	no effect to some increase	greatly increased for unweathered ash	greatly increased for unweathered, alkaline ash
soil salinization	no effect to some increase	greatly increased for unweathered ash	greatly increased for unweathered ash
soil warming	no effect	may increase slightly	increased
water infiltration	no effect to some increase for fine-textured soils	increased for most soils	may decrease
percolation	no effect to slightly reduced	reduced	reduced
chemical solubiliza-tion in soil	no effect to slightly reduced solubility of acidophilic elements, including Cd, Zn	generally reduced solubility of acidophilic elements, including Cd, Zn; increased solubility of As, B, Mo, Se	reduced solubility of acidophilic elements, including Cd, Zn; increased solubility of As, B, Mo, Se
chemical precipitation in soil	little to no effect	increased for acidophilic elements, including Cd, Zn; reduced for As, B, Mo, Se	increased for acidophilic elements, including Cd, Zn; reduced for As, B, Mo, Se
colloid generation	no effect	generally no effect; may increase if highly alkaline ash used	may increase if highly alkaline ash used; no effect if acidic ash used
compounds volatilization	no effect	may be increased for NH_4^+	increased for NH_4^+
evaporation	no effect to slightly reduced	reduced for most soils	reduced for most soils
soil aeration	slightly increased in fine-textured soils	increased in most soils	increased in most soils

Table 1-2. (continued).

Process	Impact of soil amendment at rates of: < 100 t/ha ash	100 to 400 t/ha ash	> 400 t/ha ash
wind erosion	generally no effect	slightly increased for most soils	greatly increased for most soils
root establish-ment	no effect to slightly increased in fine textured soils	generally increased when weathered ash used; may be decreased in salt- and B-sensitive plants when unweathered ash used	generally increased when weathered ash used; generally decreased when unweathered ash used
plant growth	generally improved; may decrease in plants sensitive to salt and/or B when unweathered ash used	generally improved; decreased in plants sensitive to salt and/or B when unweathered ash used	reduced in most species; plants tolerant of high salt and B levels may be unaffected
root uptake	no effect to slightly increased for most elements	generally increased for most elements except N and P; greatly increased for As, B, Mo, and Se with unweathered ash, may result in B toxicity in sensitive	generally reduced for N and P resulting in deficiency; increased for most other elements; greatly increased for As, B, Mo, and Se with unweathered ash, resulting in B toxicity in most plants
bioaccumula-tion of elements	may be slightly increased for most elements except N and P	generally increased for most elements except N and P, particularly when unweathered ash used; may have B, Mo, and Se toxicity problems in sensitive species when unweathered ash used	increased for most elements except N and P; may have As, B, Mo, and Se toxicity problems, particularly when unweathered ash used

2 CHEMICAL PROPERTIES OF FLY ASH AMENDED SOIL AND CROPS GROWN ON THEM

2.1 INTRODUCTION

Agricultural use of fly ash, a waste by-product of coal combustion, has been investigated since the 1950s when researchers discovered that fly ash contained trace elements beneficial to plants (Rees and Sidrak, 1956; Rudulph, 1956). Many fly ash review papers have since been published in which the researchers characterize its physical and chemical properties, assess its potential as a soil amendment, and identify environmental concerns (Carlson and Adriano, 1993; Sharma et al., 1989; El-Mogazi et al., 1988; Adriano et al., 1980; Page et al., 1979). However, fly ash research continues due to: d veloping waste disposal concerns, source dependent variability in chemical properties, newly identified opportunities for beneficial utilization, and associated environmental concerns.

Most fly ash environmental concerns arise from its influence on chemical properties of amended soils. Of primary interest is the influence on trace element concentration, solubility, and plant availability which are related to ash elemental composition, ash pH, and soil pH. Aside from trace element leaching and groundwater contamination potential, implications to plant and subsequent animal and human nutrition are of particular interest. The excessive concentration of soluble B in unweathered fly ash accompanied by pH induced deficiency of Cu, Fe, Mn, and Zn and increased plant availability of As, Mo, Se, and V in alkaline fly ash are of primary concern (Carlson and Adriano, 1993; El-Mogazi et al., 1988). High soluble salt content is an additional concern at high application rates (Carlson and Adriano, 1993; El-Mogazi et al., 1988).

Because of the source dependent variability in chemical composition of fly ash, the effect of fly ash application has not been thoroughly evaluated in western Canada. The objective of this research was to quantify changes in trace element concentration in plants and soil on plots amended with an alkaline, unweathered, western Canadian fly ash and to assess implications for plant and animal nutrition.

2.2 MATERIALS AND METHODS

2.2.1 Site Location And Experimental Design

Our study was conducted on reclaimed land at the Highvale coal mine owned by TransAlta Utilities Corporation. The mine is located at 53.5 °N, 114.6 °W, approximately 90 km west of Edmonton, Alberta, in the Mid Boreal Mixedwood ecoregion (Strong, 1992). Mean annual precipitation for the site is 528 mm (Naeth and Chanasyk, 1993).

A randomized block design was employed in which one block was located in each of three reclaimed fields on the mine: Field 42, Field 43, and Field 45. There were six fly ash treatments (0, 25, 50, 100, 200, and 400 t/ha) and four vegetation treatments (no vegetation, barley (*Hordeum vulgare*, Jackson cv.), alfalfa (*Medicago sativa*, Beaver cv.), and smooth brome (*Bromus inermis*)) per block. The fly ash x vegetation treatments were randomly assigned totaling 24 plots in each block (Figure 2-1). The plot size was 16.6 m^2 (3.65 m x 4.55 m) with a buffer zone of 0.6 m between plots and a central corridor 3.5 m wide which separated two rows of 12 plots each.

Field 42 had been reclaimed in 1988 and Fields 43 and 45 were reclaimed in 1990. All fields had been revegetated with a forage mixture after approximately 150 cm of subsoil and 20 cm of topsoil had been replaced over the mine spoil. Subsoil and topsoil thickness may vary throughout each field. Topsoil and subsoil materials were comprised of a mixture of soil series from forest-grassland transitional Luvisolic and Solonetzic Soil Orders. These pre-disturbance soils developed on a complex distribution of saline and nonsaline glacial parent materials of varying textures derived from the Paskapoo and Edmonton geologic formations. The Edmonton formation was deposited in brackish water and subsequently soils which have developed on parent material derived from this formation often, but not always, have a high concentration of soluble sulfate salts. Thorsby, Kawood, Uncas, and Dnister are examples of soil series in the Highvale area which are derived from the Edmonton formation. The Paskapoo formation is primarily comprised of nonsaline sandstone and siltstone. The Modeste series is an example of a soil series in the Highvale mine area derived from the Paskapoo formation. As a result of soil variability, topsoil salvage included a high proportion of Solonetzic soils making these soils difficult to manage for reclamation. The topsoil in each field was a clay loam texture; the subsoil texture was clay to clay loam in Field 42, silty loam to clay loam in Field 43, and loamy sand to sandy loam in Field 45. From field observations during soil sampling, the properties of subsoil (texture) varied among plots in each field; topsoil properties were less variable.

2.2.2 Fly Ash Source And Application

Unweathered fly ash was taken from the Sundance power station on May 13 and 14, 1993. The coal source for the power station is described as sub-bituminous (A/B) coal from the Scollard member of the Tertiary and Upper Cretaceous Paskapoo geological formation. A sample of fly ash was sent to a commercial laboratory for total and water soluble elemental analyses. A known mass of fly ash was measured into a pail and spread on each plot on May 13 and 14, 1993; a rake was used to aid in spreading the low rate treatments. The fly ash was then incorporated to a depth of 10 to 15 cm by a single pass of a rototiller.

2.2.3 Soil Fertility And Seeding

Prior to seeding in 1993, for each field, one soil sample to 30 cm was taken from each of the 24 plots. For each rate of fly ash application at a given field, the four samples of that rate were combined. The six resulting samples from each field were sent to a commercial laboratory for routine soil fertility analysis and fertilizer recommendations.

The barley and alfalfa plots were seeded with a plot seeder (20-cm row spacing) on June 2, and the brome was hand broadcast on June 3, 1993. Barley was seeded at 100 kg/ha, brome at 9 kg/ha and alfalfa at 8 kg/ha. Prior to seeding, the barley was treated with Vitavax and the alfalfa was inoculated with *Rhizobium meliloti* (strain NRG185). Urea (46-0-0) and Triple Superphosphate (0-45-0) fertilizer was applied to barley and brome plots to provide 130 kg/ha of N and 30 kg/ha of P_2O_5. Alfalfa plots received 30 kg/ha N and 55 kg/ha of P_2O_5. Phosphorous was placed with seed (barley and alfalfa) and N was side banded.

In spring 1994, mine workers accidentally broadcast fertilized twelve plots in Field 42 and all plots in Field 45. The fertilizer was evenly distributed in Field 42 but unevenly distributed within plots of Field 45. The application rate was 50 kg/ha N and 18 kg/ha P_2O_5. In Field 42, the unfertilized alfalfa and brome plots were broadcast fertilized with an fertilizer rate equivalent to the accidental spreading. The brome plots in each Field were subsequently fertilized to provide a total of 100 kg/ha N and 40 kg/ha P_2O_5. The alfalfa plots were fertilized to provide a total of 40 kg/ha P_2O_5; no additional N was applied to the alfalfa. On May 24, 1994, the barley plots were again seeded with treated Jackson barley at a rate of 100 kg/ha. The plots were fertilized providing 25 kg/ha P_2O_5 with the seed and 100 kg/ha of N side banded. Fertilizer applied with barley during seeding was adjusted to compensate for the accidental fertilizer application described above.

2.2.4 Soil Sampling

In May and September 1993 and May and August 1994, composite samples consisting of three soil cores, were taken from within each plot by the following depth increments: 0 to 15, 15 to 30, 30 to 60, and 60 to 90 cm. Due to financial constraints, laboratory analysis was not done on the 30 to 90 cm depth samples for the 25, 50, 100, and 200 t/ha fly ash rate samples. Samples from the spring of each year were stored until fall when all samples were sent for analysis. Samples collected in 1993 were stored in a refrigeration unit at 4°C. Samples collected in 1994 were stored in a warehouse at room temperature. In spring 1994, 0 to 15 and 15 to 30 cm samples were taken from the control vegetation treatment at each fly ash rate for total chemical analysis. To reduce analytical costs, samples of the same rate from each of the three fields were mixed to provide one composite sample.

2.2.5 Vegetation Plot Maintenance And Sampling

We collected three 0.1 m^2 whole plant silage samples (soft dough stage) from randomly located areas within each barley plot on August 16, 1993. The plants were clipped 5 cm above ground and, fresh and dry weights were determined. The three replicate samples from each plot were combined for chemical analysis. On September 7, 1993, the mature barley on each plot was cut, air dried, and threshed. Straw and grain samples were collected for chemical analysis. For weed control in 1994, the reseeded barley plots were sprayed with cyanazine on June 3. In 1994, harvest of barley at boot stage on July 12, soft dough stage on August 2, and maturity on August 16 was conducted as described for 1993.

On September 7, 1993, whole alfalfa plants were clipped in two rows (3.7 m long) from each plot. None of the plants had reached 10% bloom stage although some plants were beginning to flower. Several plots in Field 42 were damaged by extended saturated soil conditions. In spring 1994, wet conditions prevented early weed control. On June 3, the plots were sprayed with sethoxydim herbicide. All alfalfa plots suffered from herbicide stress. However, within 3 weeks plants seemed to have recovered fully. On June 21 and again on August 9, 1994, several whole plants were randomly removed from each plot as samples for elemental analysis followed by complete plot harvest. The alfalfa was at 10% bloom on both sampling dates in 1994.

On September 7, 1993, whole plant samples of brome were collected, washed, sorted, and sent for analysis. The most mature brome had just entered heading at the time of sampling. On June 21 1994, several whole plants at anthesis stage were randomly removed from throughout each plot for analysis.

Plant samples were washed to remove chemical contamination from dust. All plant samples except barley grain and straw were washed briefly in mild soapy water using phosphate free dish soap followed by two rinses with distilled water and one rinse with deionized water. Barley straw was not washed due to the risk of washing chemical elements out of the dry plant tissue. Samples were then oven dried at a temperature of 50 °C and sent to a commercial laboratory for chemical analysis.

2.2.6 Soil And Plant Laboratory Analysis

Plant samples were block digested using 2 parts concentration HNO_3 and 1 part concentration $HClO_4$ to white fumes of $HClO_4$ (Bock, 1979). Metals analysis conducted by ICP according to Environmental Protection Agency (EPA) Method 6010A for Na, P, K, S, Ca, Mg, Cu, Fe, Mn, Zn, B; As and Se were analyzed by hydride using: EPA Method 7061A for As and EPA Method 7741A for Se (Environmental Protection Agency).

Soluble metals in the soil (As, B, Ba, Cr, Cu, Mn, Mo, P, S, Se, Sr, Zn) were extracted according to Canadian General Standards Board Leachate Extraction Procedure with the modification that Ultra Pure Water was used as the extractant. Saturated paste extract (McKeague, 1978) was used to determine saturation percentage (SAT%), Ca, Mg, Na, K, Fe, and Al. All metal analysis was done by ICP according to EPA Method 6010A except: As by EPA Method 7061A and Se by EPA Method 7741A (Environmental Protection Agency). Total chemical analysis was determined by strong acid digestion using Aqua Regia/Perchloric (Bock, 1979). Soil pH was measured by saturated paste and electrical conductivity (EC) and was measured by saturation paste extract (McKeague, 1978). All of the afore mentioned soil and plant chemical analysis was done by Plains Innovative Laboratory Services (ad division of EnviroTest Labs) in Saskatoon, Saskatchewan.

2.2.7 Time Dependent Electrical Conductivity

A completely randomized design was used in a laboratory experiment to monitor change in EC over time under saturated conditions. Three replicates of five fly ash/soil treatments (0, 10, 20, 40, and 100% fly ash) were prepared and subsequently mixed with water on a 1:1 mass basis. Clay loam textured topsoil from Field 45 was used. Samples were stirred and allowed to settle for one hour prior to extraction of a minimal amount of solution for EC measurement. Solution was returned to the soil:solution mixture in the sample beaker after EC had been measured. EC readings were taken at 0, 1, 2, 4, 8, 16, and 32 days after mixing. To compensate for evaporation loss, the beakers were weighed early in the experiment and on each following measurement date sufficient water was added to bring the beaker and contents to original mass; the beakers were covered with parafilm.

2.2.8 Statistical Methods

Statistical significance was determined using Fisher's Protected Least Significant Difference (FPLSD) for all variables except for the laboratory EC experiment (Steel and Torrie, 1980). Using FPLSD, a mean comparison (i.e. the LSD) can only be completed if the Probability > F (Prob>F) calculated from the ANOVA is ≤ 0.05. In the laboratory EC experiment, a split-plot in time analysis was used (Steel and Torrie, 1980). The 100% treatment was excluded from statistical analysis in the EC experiment to permit more meaningful interpretation of differences among the other four treatments. Statistical analysis was not conducted on total chemical analysis data due to lack of replication.

2.3 RESULTS AND DISCUSSION

The data from the various chemical analysis are presented in Tables 2-1 to 2-6 and Figure 2-1. They are discussed in the following subsections

2.3.1 Chemistry Of Fly Ash And Soil

A summary of total and water soluble chemical analyses compared with crustal abundance and our soil values is provided in Table 2-1. Elemental crustal abundance charts are frequently used as a standard to compare with values measured in soil. Soil elemental values are usually considered normal if they are within an order of magnitude of crustal values (M. Dudas, 1994, personal communication, Professor, Department of Renewable Resources, University of Alberta). Special management may be required for soils which contain a trace element(s) that is more than one order of magnitude different from crustal abundance values. Soils having a trace element content being a difference greater than one order of magnitude may require special management. Total and water soluble content of B, Ca, Mo, and Se were considerably greater in fly ash than crustal abundance and shale values.

A summary of statistically significant trends from chemical analysis is presented in Table 2-2. There were consistent significant increases in water soluble contents of several elements with increase in fly ash rate (Table 2-2). However, soluble Fe and Al consistently decreased as fly ash rate increased. Data for water soluble elemental analysis of Ca, Na, Mg, B, Se, and Mo, soluble Na:Ca ratio, and soil pH are provided in Table 2-3. At the 15-30 cm depth, there was no statistically significant difference among fly ash treatments prior to the fall 1994 sample date. Further discussion of specific elements is provided later in this section. A summary of statistical analysis for all trace elements measured is provided in Appendix 6.1.

The EC of fly ash was 13 dS m^{-1} (sat. paste). Despite this, the EC of soil was less than 1 dS m^{-1} for all treatments on all field sampling dates. Results of the laboratory evaluation of EC change with time are shown in Figure 2-2. The ECs of the 0, 10, 20, and 40% fly ash treatments were significantly different at each observation time except at 16 d. At 16 d, no significant difference was observed between the 20 and 40% treatments. ECs of the 20 and 40% treatments are considered slightly saline. EC of the 100% treatment, was initially much higher than other treatments (severely saline), but decreased to lower levels (slightly saline) after 32 d. This decrease in EC is related to the chemical reactions of CaO with OH^- and CO_2. Initially the high concentration of CaO in fly ash would increase EC due to its high solubility. Upon reacting with water and carbon dioxide, CaO forms $CaCO_3$ which has a low solubility and thus a low EC. Page et al. (1979) found that salt content in a 1:1 fly ash:water extract, was reduced by 30% after a 30 day equilibration period.

Spring 1993 soil pH increased significantly with fly ash amendment from 6.1 for the 0 t/ha treatment to 7.8 for 400 t/ha (Table 2-3). All fly ash treatments had a significantly higher pH than the 0 t/ha treatment. Our observations of increase in soil pH with fly ash rate support the findings of other researchers (Carlson and Adriano, 1993; Pluth et al., 1981).

The total concentration of B in the surface soil (Table 2-1) was within the range typical for the Edmonton region (20 and 30 ug/g) (Pawluk and Bayrock, 1969). Total soil B concentration increased with fly ash rate from 26 ug/g to 66 ug/g. The percentage of soluble B in the fly ash (19% of total) was similar to that for soil (17% of total) although unamended soil values were expected to be much lower (~5%) (El-Mogazi et al., 1988). In spring 1993, soluble B concentration as a percentage of unamended soil concentration was 118% for the 25 and 50 t/ha, 143% for 100 t/ha, 191% for 200 t/ha, and 304% for the 400 t/ha treatment. On all sample dates except spring 1994, water soluble B increased significantly with fly ash rate at the 0 to 15 cm depth (Table 2-3). At 15 to 30 cm, no statistically significant differences in soluble B among treatments was observed until fall 1994 when soluble B concentration increased with increasing fly ash. The decrease in B content with time at the 0 to 15 cm depth indicates that B was leached from the topsoil and/or was removed by plants.

Alberta Agriculture (1992) suggests the following classification for B levels (hot water extractable - ug/g) in soils: Deficient 0.0-0.4, Medium 0.5 to 1.2, Adequate >1.2 and Reisenauer et al. (1973) reported that a concentration of >5 ug/g B is toxic to some plants. Most crops grown on fly ash amended soils show signs of toxicity if hot water extractable B exceeds 20 ug/g; some sensitive crops, may exhibit toxicity symptoms if hot water extractable B exceeds 7 ug/g (Adriano et al., 1980). Based on these guidelines the water soluble concentration of B for the 0 to 15 cm depth increment exceeded critical concentrations in 1993.

Total Ca content in fly ash was 8 times higher than the unamended soil. Water soluble Ca of fly ash was 8% of total Ca compared with <1% for unamended soil. Total Ca in soil was considerably lower than crustal and shale values (Table 2-1). For the spring 1993 samples, water soluble Ca increased from 91 ug/g for 0 t/ha to 450 ug/g for the 400 t/ha treatment. Typical Ca levels in solution of temperate region soils range from 30 to 300 ug/g (Tisdale et al., 1985). Reduced B availability and uptake by plants has been correlated with the concentration of free Ca ions in the soil (Reisenauer et al., 1973; Flemming, 1980), although this correlation may also be pH related (Gupta et al., 1985). Criteria for Ca toxicity to plants have not been reported in literature; critical Ca deficiency criteria are related to soil pH and plant species. Increased Ca availability in soil is beneficial for most agronomic species.

The soluble Na:Ca ratio of fly ash amended soils decreased with increased fly ash rate from a maximum of 3.1 for 0 t/ha to a minimum of 0.8 for 400 t/ha (Table 2-3). The low Na:Ca ratio of fly ash from the Sundance power station has been previously recognized, however, this characteristic is not consistent among other power stations in Alberta (Pluth et al., 1981). Reduction in clay dispersion and soil crusting associated with an improved (lower) Na:Ca ratio was observed (but not quantified) in this field study.

Soluble Mg concentration increased with addition of fly ash. These results were unexpected since the total and water soluble Mg content of fly ash was very similar to that of soil.

Soluble Mo concentration increased with fly ash rate in 1993 (Table 2-3). Increasing solubility of Mo with pH increase (Reisenauer, 1973; Adriano et al., 1986), and the high concentration of total and soluble Mo in fly ash (Table 2-1) account for this trend.

2.3.2 Trace Element Content In Plants

The results of chemical analysis of plant materials are presented in Tables 2-4 and 2-5. Summaries for the various tables follow. The data for barley are limited because of flooding, bird damage and the diseases barley scald and stripe. Thus we will primarily focus on results from the barley soft dough and boot stages.

Statistically significant trends in trace element content of the vegetation treatments varied depending upon plant species, stage of development and plant (Table 2-4). Of particular importance is the observed increase in B and Mo with increase in fly ash rate. Data for N, P, Ca, B, Cu, Mo, Se, and S are shown in Table 2-5. Data for the remaining elements is provided in Appendix 6.2.

The total concentration of B increased with fly ash amendment for all plant treatments except barley grain and straw in 1994 (Table 2-4). The 25 and 50 t/ha treatments were rarely significantly different from the 0 t/ha treatment for any crop. The B content of the 400 t/ha treatment was significantly higher than the 0 t/ha treatment for each crop except 1994 barley grain and straw. Boron concentration in the vegetation was considerably lower in the second year of our study. El-Mogazi et al. (1988) reported similar time related trends, however, our results may also be related to disease problems in barley and differences in stage of plant development for alfalfa and brome.

An understanding of B requirements by crops can provide an indication of the relative tolerance of various crops to B toxicity. The B requirement of brome and barley generally are low whereas alfalfa has a high B requirement (Flemming, 1980). Boron toxicity under field conditions generally occurs when plant tissue concentration exceeds 200 ug/g (Gupta et al., 1985), but the critical concentration is species dependent. Reuter and Robinson (1986) reported that B concentrations exceeding 40 ug/g in barley at boot stage was toxic to the plant. Based on this guideline, B toxicity symptoms should not have been apparent in the 1994 barley at boot stage except on the 400 t/ha treatment. High B concentration in vegetation may also be toxic to livestock. In 1993, the mean B content of barley at soft dough stage was 150 ug/g on the 400 t/ha treatment. This high B content jeopardizes the suitability of barley silage as feed for livestock (McDowell, 1992).

For most vegetation treatments, we observed no statistically significant difference in N and P concentration among fly ash treatments, however, a trend of increasing concentration of N and P with fly ash rate was evident (Table 2-5). N concentration typically peaked for the 400 t/ha treatment; peaks in P concentration varied among vegetation treatments. High N concentration in plant material is typically an indicator of stress in plants. Opposite trends in N were observed between the two cuts of alfalfa in 1994. S and K trends varied among vegetation treatments.

In 1994 alfalfa, Cu and Zn concentrations were marginal and becoming increasingly deficient as fly ash rate increased; Mn uptake was marginal for treatments exceeding 50 t/ha (Alberta Agriculture, 1992). These results support findings of other researchers (Carlson and Adriano, 1993). No deficiency symptoms were apparent in the alfalfa. Micronutrient concentration was adequate for all barley treatments.

We observed significant increases in Mo concentration with increase in fly ash rate for the alfalfa, barley straw, and brome treatments in 1993 and all vegetation treatments in 1994 (Table 2-5). These results support findings of other researchers (Sharma et al., 1989). The fly ash rate of lowest significant influence on Mo concentration ranged from as low as 25 t/ha fly ash for alfalfa in 1993 to 200 t/ha for barley straw. Concerns regarding molybdenosis disease in livestock is warranted due to an upset Cu:Mo ratio in vegetation. Critical Cu:Mo ratios in feed range from 2:1 to 2.8:1; a Cu:Mo ratio of 4:1 has been proposed to ensure the Cu requirement is met (McDowell, 1992). Most 0 t/ha treatments had a ratio of >3:1. Cu:Mo ratios below critical levels were observed for fly ash treatments as low as 25 t/ha (1994 alfalfa); Cu:Mo ratios below 1:1 were prevalent for most 400 t/ha treatment. The upset Cu:Mo balance in plant tissue is a result of increased Mo availability in the soil and, to a lesser extent, soil pH related decrease in Cu availability. We observed no indication of a time related decrease in plant uptake of Mo which supports the findings presented by El-Mogazi et al. (1988). Despite sufficient concentration of Cu for plant nutrition (Alberta Agriculture, 1992), a Cu feed supplement would need to accompany feed grown on fly ash amended soils to meet nutritional requirements of livestock.

Se is not essential to plant growth and the observed concentration in vegetation treatments does not indicate any possibility of Se toxicity (McDowell, 1992). Se is, however, of great importance in human and animal nutrition. The dietary Se requirements of beef cattle is 0.2 ug/g and for dairy cattle is 0.1 ug/g (Combs and Combs, 1986). In 1993, we observed a significant increase in Se concentration with fly ash rate for alfalfa, barley straw, and brome; a similar although not significant trend was observed for the remaining treatments (Table 2-5). In each of these vegetation treatments the Se concentration of the 0 t/ha treatment did not meet the dietary Se requirements of beef cattle. This requirement was met with the application of 100 t/ha of fly ash to the alfalfa, 200 t/ha to the barley, and 50 t/ha to the brome. We observed no significant influence on Se concentration in vegetation in 1994 aside from an inconsistent trend in the second cut of alfalfa.

Trends in Sr, Mg, Cr, and Na, content with fly ash rate are of little biological significance (Reuter and Robinson, 1986).

2.3.3 Common Trends In Soil And Plant Analysis

Elements with common statistically significant trends in both the soil and plants are shown in Table 2-6. Of all elements, trends of only B, Mo, Se, and possibly Ca are statistically and biologically significant; only B reached concentrations regarded toxic to plants. Interest in Mo and Se is associated with animal nutrition concerns; high B concentration observed in the 400 t/ha barley silage treatment from 1993 is also of concern for animal nutrition.

2.4 CONCLUSIONS

The application of fly ash as a soil amendment increased the concentration of water soluble B in the soil to levels which were toxic for barley and brome grass with increasing toxicity with increasing fly ash rate. The concentration of water soluble B in topsoil decreased with time as a result of leaching and plant uptake. Se concentration in livestock feed was increased from deficient to adequate concentrations by increasing plant available Se with fly ash application. Due to a fly ash related increase in plant available Mo and a subsequent decrease in livestock dietary Cu:Mo ratio, there is an increased risk of molybdenosis disease in cattle feeding on vegetation from fly ash amended soils. Plant available Mo did not decline after two growing seasons. The fly ash amendment increased soil pH and plant available Ca, and decreased the soluble Na:Ca ratio of the soil. Fly ash had no influence on electrical conductivity at five months after application. Based on this two year study and the chemical properties of fly ash described above, the maximum acceptable rate of unweathered fly ash application for plant growth on a clay loam textured soil is less than 200 t/ha. For livestock diets exclusive to crops grown on fly ash amended soil, the maximum acceptable fly ash application rate is < 50 t/ha if a dietary Cu supplement is not provided.

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Table 2-1. Water soluble and total content (ug/g) of selected elements in fly ash, soil, and total crustal and shale values from the literature.

Element	Fly Ash[†] Total	Fly Ash[†] Water Soluble	Soil[†] Total	Soil[†] Water Soluble	Crustal[‡] Total	Shale[‡] Total
Al	72000	112	72814	0.12	82000	80000
As	12	0.024	<6	0.04	1.8	6.6
B	160	30	25.6	4.4	10	100
Ba	3000	84	nd[§]	6.8	425	580
Ca	70000	5400	8292	30	41000	25000
Cd	<1	<0.1	nd	nd	0.2	0.3
Co	11	<0.1	nd	nd	25	20
Cr	25	1.7	nd	0.03	100	100
Cu	22	<0.1	18.5	0.10	55	57
Fe	18000	<0.1	32824	0.27	56000	47000
Hg	0.37	0.0044	nd	nd	0.08	0.4
K	690	4	nd	2.3	21000	23000
Mg	3900	2	5730	7	23000	13400
Mn	250	<0.1	353	4.4	950	850
Mo	19	4.2	<2	0.29	1.5	2.0
Na	10000	220	2551	93	24000	6600
Ni	16	<0.1	nd	nd	75	95
P	320	<4	474	2.6	1050	770
Pb	74	<0.4	24	0.04	12.5	20
Se	4	0.4	<30	<2	0.05	0.6
Sr	660	76	nd	3.9	375	450
Ti	1700	<0.1	nd	nd	5700	4500
V	46	<0.1	nd	nd	135	130
Zn	34	<0.1	111	0.5	70	80

[†] Soil and fly ash data are from this study

[‡] Average total values for Earth's crust and shale. A deviation of one order of magnitude or greater from these average values is indicative of 'unique' soil properties (Krauskopf (1979))

[§] nd - no data

Table 2-2. Water soluble elements and pH in soil with statistically significant (α=0.05) differences among fly ash treatments and their trend in relation to fly ash rate increase.

Sample Period/Depth	Increasing	Decreasing
0-15 cm		
Spring 1993	B, Ca, Cr, Mg, Mo, Na, pH	Fe, Al
Fall 1993	B, Ca, Cr, K, Mg, Mo, Na, P, Se, pH	Fe, Al
Spring 1994	Ca, Mg, Na, P, Se, Sr, pH	Fe, Al, Mn
Fall 1994	B, Ca, Mg, Na, P, Se, Sr, pH	Fe, Al
15-30 cm		
Fall 1994	B, Ca, Mg	Al

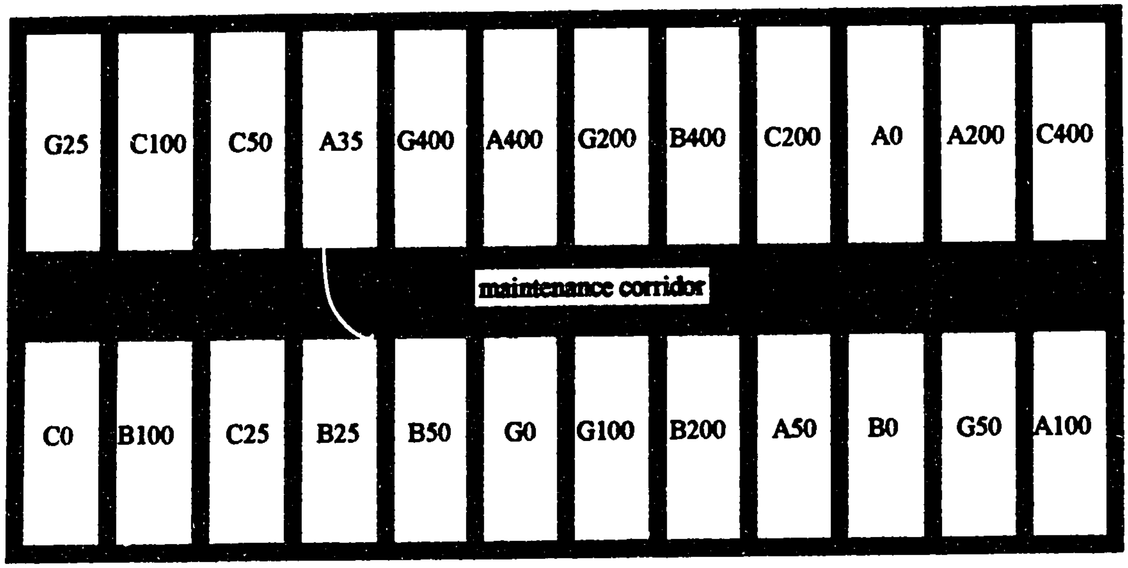

Figure 2-1. Diagram of Field 43 plot layout showing vegetation and fly ash treatments where A is alfalfa, B is barley, C is control, G is brome grass and 0, 25, 50, 100, 200, 400 represent fly ash rate in t/ha.

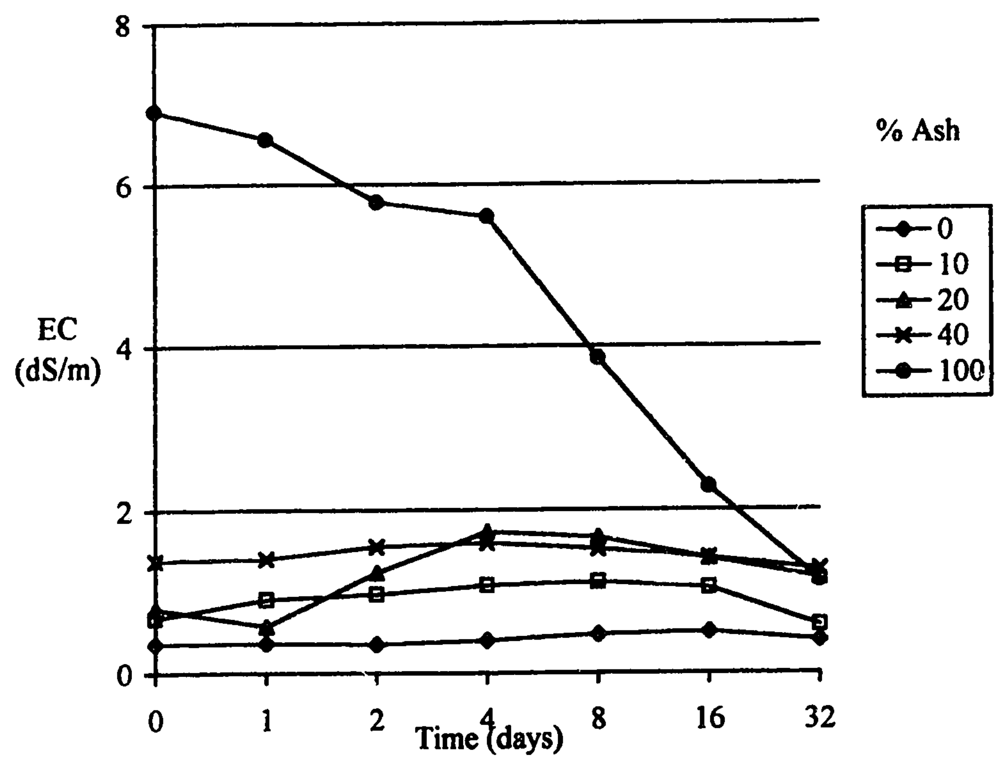

Figure 2-2. Electrical conductivity of 1:1 soil/fly ash:water mixture with time.

Table 2-3. Water soluble elemental analysis (ug/g), Na:Ca ratio, and soil pH of fly ash amended plots in 1993 and 1994.†‡

Fly Ash (t/ha)	pH	Na:Ca	Ca	Na	Mg	B	B§	Se	Mo
Spring 1993									
0	6.1 d	3.1	91 d	282 c	20 d	4.4 d	1.1	0.000	0.29 b
25	6.8 c	1.8	186 cd	328 bc	44 bc	5.2 cd	0.9	0.000	0.38 b
50	6.4 cd	2.0	158 cd	310 bc	33 cd	5.1 cd	1.0	0.003	0.33 b
100	6.7 c	1.5	244 bc	358 ab	48 bc	6.3 c	0.9	0.000	0.41 b
200	7.3 b	1.4	294 b	417 a	52 ab	8.4 b	0.9	0.002	0.44 b
400	7.8 a	0.9	485 a	426 a	69 a	13.3 a	1.5	0.006	0.71 a
Prob>F	0.00	-	0.00	0.00	0.00	0.00	0.77	0.41	0.00
Fall 1993									
0	6.2 c	2.6	84 e	217 c	17 e	2.2 d	0.5	0.001 b	0.01 d
25	6.8 b	1.6	147 de	236 c	27 de	2.6 cd	0.5	0.001 b	0.03 d
50	6.9 b	1.3	207 cd	273 bc	34 cd	2.6 cd	0.7	0.001 b	0.05 cd
100	7.1 b	1.1	280 bc	300 b	44 bc	4.3 bc	0.4	0.001 b	0.14 c
200	7.6 a	1.1	342 b	390 a	51 ab	5.9 b	0.7	0.004 a	0.26 b
400	7.6 a	0.8	505 a	419 a	66 a	10.1 a	0.6	0.007 a	0.49 a
Prob>F	0.00	-	0.00	0.00	0.00	0.00	0.85	0.00	0.00
Spring 1994									
0	6.0 c	2.45	120 d	293 cd	23.7 c	3.9	4.1	0.066 b	nd¶
25	6.8 b	1.36	193 cd	263 d	33.1 bc	4.6	4.1	0.075 b	
50	6.7 b	1.22	241 bc	295 cd	42.5 ab	4.4	4.2	0.067 b	
100	7.1 b	1.01	325 b	328 bc	54.8 a	3.9	3.8	0.093 b	
200	7.7 a	1.06	382 ab	404 ab	64.6 a	4.9	4.2	0.101 b	
400	8.0 a	0.81	516 a	417 a	69.3 a	5.8	4.0	0.177 a	
Prob>F	0.00	-	0.00	0.00	0.00	0.08	0.99	0.00	
Fall 1994									
0	6.4 c	3.21	65 c	210 c	16.2 c	1.2 c	1.1 c	0.072 b	nd
25	7.0 b	1.59	131 bc	208 c	24.1 bc	1.2 c	1.1 c	0.121 b	
50	6.8 bc	2.26	101 bc	229 bc	20.9 bc	1.6 bc	1.3 bc	0.088 b	
100	7.2 b	1.58	165 b	261 abc	31.2 ab	1.6 bc	1.5 abc	0.107 b	
200	7.9 a	1.74	174 ab	301 ab	33.4 ab	2.1 ab	1.6 ab	0.111 b	
400	7.9 a	1.33	264 a	351 a	42.9 a	2.9 a	1.9 a	0.183 a	
Prob>F	0.00	-	0.00	0.00	0.02	0.00	0.01	0.01	

† All data from 0-15 cm depth unless otherwise noted

‡ On each sampling date, means within a column followed by the same letter are not significantly different (α=0.05)

§ Data from 15-30 cm depth

¶ nd - non-detectable

Table 2-4. Total elements and acid digestible fibre of vegetation treatments with statistically significant (α=0.05) differences among fly ash treatments and their trend in relation to fly ash rate increase.

	Increase	Decrease	Other[†]
1993			
Alfalfa	B, Se		Cu, Mo, ADF[‡]
Barley, Soft Dough	B, Ca, Mg, P		As
Barley, Grain	B, S		
Barley, Straw	B, Ca, Cu, Mg, Mo, N, P, Se, Sr	ADF	K
Brome	B, Mg, Mo, P, Se, Sr		Mn
1994			
Alfalfa, Cut 1	B, Mo, N	Cu	Cr
Alfalfa, Cut 2	B, Mo	N	P, Se
Barley, Boot	B, Ca, Mo, P, Sr		ADF, Na
Barley, Soft Dough	B, Mo		Mg, Na
Barley, Grain	Mo		Ba, Cr
Barley, Straw	Mo	Cu	ADF, Cr
Brome	B, Mo, Sr		

[†] Significant difference among treatments but trend does not increase nor decrease with increase in fly ash amendment - highest values may be at intermediate rates

[‡] acid digestible fibre

Table 2-5. Selected chemical analysis data for various plant materials on fly ash amended plots. †

Fly Ash (t/ha)	N (%)	P (%)	Ca (%)	B (ug/g)	Cu (ug/g)	Mo (ug/g)	S (%)	Se (ug/g)
Alfalfa, 1993								
0	4.1	0.28	1.93	49 b	9.6 b	1.7 d	0.43	0.03 d
25	3.8	0.26	1.85	59 b	12.6 a	5.7 c	0.37	0.09 cd
50	3.9	0.29	1.76	56 b	9.6 b	7.7 bc	0.39	0.12 bcd
100	4.1	0.30	1.74	60 b	9.4 b	10.2 b	0.40	0.33 ab
200	4.1	0.30	1.88	90 ab	9.6 b	14.5 a	0.43	0.30 abc
400	4.1	0.26	1.89	139 a	8.9 b	8.5 bc	0.44	0.36 a
Prob>F	0.80	0.10	0.30	0.03	0.04	0.00	0.12	0.03
Barley Silage, 1993								
0	1.67	0.12 d	0.31 d	1 c	5.4 a	0.0	0.29	0.19
25	1.58	0.13 cd	0.33 cd	12 c	5.3	0.0	0.33	0.15
50	1.83	0.17 bc	0.34 bcd	10 c	6.1	1.5	0.28	0.26
100	2.08	0.19 ab	0.45 abc	42 bc	6.1	2.7	0.31	0.29
200	2.09	0.16 bcd	0.46 ab	84 b	6.1	4.5	0.35	0.32
400	2.57	0.23 a	0.51 a	150 a	6.4	2.7	0.34	0.43
Prob>F	0.10	0.00	0.02	0.00	0.45	0.09	0.70	0.19
Barley Straw, 1993								
0	0.80 b	0.07 b	0.35 b	5 c	4.6 b	0.0 b	0.29 bcd	0.02 b
25	0.63 b	0.08 b	0.34 b	11 c	3.6 c	1.3 b	0.22 d	0.07 b
50	1.09 b	0.09 b	0.41 b	15 c	4.0 bc	0.0 b	0.25 cd	0.14 b
100	1.01 b	0.10 b	0.46 b	26 c	4.5 bc	1.7 b	0.33 abc	0.14 b
200	1.15 b	0.12 b	0.61 a	68 b	4.8 b	7.1 a	0.39 a	0.28 b
400	1.82 a	0.18 a	0.67 a	119 a	6.0 a	5.6 a	0.38 ab	0.58 a
Prob>F	0.03	0.01	0.00	0.00	0.01	0.00	0.01	0.00
Barley Grain, 1993								
0	1.90	0.29	0.04	0 b	10.4	0.0	0.15 c	0.24
25	1.85	0.31	0.04	0 b	9.2	0.3	0.15 c	0.30
50	1.84	0.32	0.05	1 b	12.2	0.3	0.14 c	0.38
100	1.94	0.33	0.04	1 b	10.6	0.5	0.15 c	0.25
200	2.14	0.34	0.05	8 ab	8.1	1.4	0.17 b	0.33
400	2.24	0.39	0.06	12 a	10.6	0.3	0.18 a	0.44
Prob>F	0.06	0.28	0.07	0.05	0.76	0.47	0.00	0.22

Table 5. (continued).

Fly Ash (t/ha)	N (%)	P (%)	Ca (%)	B (ug/g)	Cu (ug/g)	Mo (ug/g)	S (%)	Se (ug/g)
Brome, 1993								
0	4.59	0.30 c	0.44	9 d	13.2	0.0 c	0.41	0.12 d
25	4.55	0.30 c	0.45	13 cd	14.4	0.7 c	0.45	0.10 d
50	4.63	0.31 c	0.47	30 bc	10.9	2.5 bc	0.42	0.20 cd
100	4.52	0.32 bc	0.48	33 b	12.9	3.7 abc	0.46	0.34 bc
200	5.18	0.36 a	0.50	45 b	13.8	5.5 ab	0.45	0.47 ab
400	5.41	0.35 ab	0.55	78 a	13.1	6.7 a	0.46	0.56 a
Prob>F	0.07	0.01	0.10	0.00	0.17	0.02	0.49	0.00
Alfalfa Cut 1, 1994								
0	2.52 c	0.17	1.14	64 d	7.0 a	1.9 c	0.31	0.46
25	2.68 bc	0.17	1.16	69 cd	6.1 abc	2.5 bc	0.29	0.22
50	2.92 ab	0.18	1.17	71 cd	6.7 ab	3.3 bc	0.32	0.52
100	2.90 ab	0.19	1.08	74 c	5.8 bc	3.9 b	0.30	0.29
200	2.94 ab	0.19	1.05	94 b	6.0 bc	8.1 a	0.30	0.48
400	2.99 a	0.17	1.17	115 a	5.5 c	6.8 a	0.28	0.31
Prob>F	0.02	0.16	0.40	0.00	0.05	0.00	0.53	0.19
Alfalfa Cut 2, 1994								
0	3.31 a	0.17 b	1.04	64 c	7.6	2.7 c	0.32 bc	0.14 bc
25	3.25 ab	0.18 ab	1.06	70 bc	7.4	3.1 bc	0.35 a	0.36 a
50	3.17 ab	0.19 a	1.00	70 bc	7.5	3.6 bc	0.34 c	0.45 c
100	2.94 bc	0.17 b	1.00	76 b	6.7	4.3 b	0.30 abc	0.19 abc
200	3.03 abc	0.18 a	0.97	80 b	7.1	5.9 a	0.32 c	0.41 c
400	2.81 c	0.18 ab	1.01	97 a	7.0	6.5 a	0.31 ab	0.31 ab
Prob>F	0.05	0.04	0.53	0.00	0.45	0.00	0.01	0.02
Barley Boot, 1994								
0	2.78	0.23 c	0.24 d	18 b	7.8	1.2 c	0.31	0.00
25	2.80	0.26 bc	0.25 cd	22 b	7.1	1.5 c	0.25	0.27
50	2.61	0.26 bc	0.29 bcd	22 b	8.0	2.4 bc	0.29	0.00
100	3.07	0.29 ab	0.31 bc	31 b	7.7	3.7 b	0.29	0.16
200	3.14	0.28 ab	0.32 b	35 b	7.5	5.3 a	0.28	0.29
400	3.63	0.31 a	0.42 a	71 a	6.7	6.2 a	0.28	0.20
Prob>F	0.13	0.02	0.00	0.00	0.69	0.00	0.31	0.81

Table 5. (continued).

Fly Ash (t/ha)	N (%)	P (%)	Ca (%)	B (ug/g)	Cu (ug/g)	Mo (ug/g)	S (%)	Se (ug/g)
Barley Soft Dough, 1994								
0	2.21	0.18	0.19	37 c	6.6	1.3 d	0.21	0.00
25	2.19	0.19	0.22	43 bc	5.7	1.6 d	0.22	0.00
50	2.13	0.19	0.24	47 bc	5.8	1.8 cd	0.21	0.00
100	2.37	0.22	0.25	58 b	6.4	3.0 c	0.23	0.51
200	2.29	0.20	0.25	62 b	5.5	4.7 b	0.23	0.00
400	2.58	0.20	0.31	106 a	5.2	6.9 a	0.24	0.14
Prob>F	0.44	0.32	0.06	0.00	0.21	0.00	0.25	0.54
Barley Straw, 1994								
0	1.34	0.15	0.16	51	5.9 a	1.5 b	0.18	0.19
25	1.17	0.13	0.18	42	4.8 ab	1.4 b	0.17	0.13
50	1.04	0.12	0.21	45	4.6 b	1.7 b	0.17	0.23
100	1.18	0.12	0.17	49	4.6 b	2.6 b	0.17	0.18
200	1.08	0.11	0.18	46	4.2 b	4.4 a	0.18	0.31
400	1.60	0.12	0.25	74	3.7 b	5.4 a	0.18	0.23
Prob>F	0.24	0.69	0.44	0.11	0.04	0.00	0.85	0.55
Barley Grain, 1994								
0	1.65	0.33	0.04	38	10.8	1.1 d	0.14 c	0.39
25	1.57	0.34	0.05	39	10.6	1.3 d	0.15 bc	0.24
50	1.52	0.36	0.04	37	10.2	1.4 cd	0.15 bc	0.34
100	1.73	0.36	0.05	40	10.8	2.0 bc	0.15 bc	0.40
200	1.77	0.38	0.04	42	12.0	2.5 b	0.16 b	0.28
400	2.09	0.36	0.05	45	8.8	3.6 a	0.17 a	0.30
Prob>F	0.10	0.31	0.11	0.08	0.35	0.00	0.01	0.94
Brome, 1994								
0	1.49	0.11	0.14 b	48 d	4.1	1.1 d	0.13	0.17
25	1.48	0.12	0.14 b	51 d	4.1	1.4 cd	0.14	0.17
50	1.76	0.12	0.15 b	57 cd	4.5	1.5 cd	0.15	0.19
100	1.59	0.13	0.14 b	60 c	4.0	2.3 b	0.14	0.15
200	1.72	0.13	0.16 b	72 b	4.3	2.1 bc	0.15	0.10
400	2.12	0.14	0.22 a	95 a	5.2	3.3 a	0.18	0.23
Prob>F	0.12	0.26	0.02	0.00	0.09	0.00	0.07	0.77

† Means within a column on each sampling date followed by the same letter are not significantly different (α=0.05)

Table 2-6. Elements with consistent significant increases or decreases in both plant materials and soils as a result of fly ash treatments. †

1993	Soil Sample Period				1994
Vegetation	Spring	Fall	Spring	Fall	Vegetation
Alfalfa	B	B, Se		B	Alfalfa, Cut 1
				B	Alfalfa, Cut 2
			Ca, P, Sr, Na	B, Ca, Sr, Na	Barley, Boot
Barley, Soft Dough	B, Ca, Mg	B, Ca, Mg, Mo, P	Na	B, Na	Barley, Soft Dough
Barley, Grain	B	B			Barley, Grain
Barley, Straw	B, Ca, Mg, Mo	B, Ca, Mg, Mo, P, Se			Barley, Straw
Brome	B, Mg, Mo, Se	B, Mg, Mo, P, Se	Sr	B, Sr	Brome

† All trends for these elements were increasing with increase in fly ash rate in both soil and plant material

3. GROWTH AND DEVELOPMENT OF BARLEY, ALFALFA, AND BROME ON FLY ASH AMENDED PLOTS

3.1 INTRODUCTION

The success of field application of fly ash as a soil amendment is related to a profitable yield increase. El-Mogazi et al. (1988) summarized reported trends in crop yield on fly ash amended soils. Yield decrease was most commonly related to boron (B) toxicity but was also related to induced phosphorus (P) deficiency, salt injury, pozzolanic (cementing) effects, and heavy metal toxicity. Yield increase resulted from correction of nutrient deficiencies, neutralizing soil acidity, or a combination of pH adjustment and nutrient supplement. However, no reliable indication of fly ash influence on crop yield in Alberta could be determined due to the variability and site dependency of these observations.

From a greenhouse study utilizing western Canadian fly ash sources, Pluth et al. (1981) found a fly ash source dependent significant increase in barley biomass with the application of fly ash to an acidic soil. A 15% Sundance fly ash treatment had a significantly higher yield than a 30% Sundance fly ash treatment. Boron toxicity symptoms were observed on the fly ash amended treatments.

In a greenhouse experiment, Lutwick et al. (1981) measured barley and alfalfa yield response to 0, 2.5, 5, and 10% fly ash mixed with problem soils. Yield of barley and alfalfa decreased with fly ash addition to an alkaline Solonetz soil, and, no yield difference was observed in the fly ash amended acidic Solonetz soil. B toxicity was observed in barley for all fly ash treatments. From this study, Lutwick et al. (1981) suggested that fly ash has greater potential to amend the physical and chemical properties of acidic soils than of alkaline soils, and that higher rates of ash application were probably needed to significantly improve the physical properties of sodic soils. However, in a bottom ash study, Natsukoshi (1981) found that greenhouse research could yield opposite results from field research based on productivity and quality of plant tissue produced. Positive results with bottom ash amendment were obtained in the field.

In this project we studied the influence of fly ash on many yield determining factors including soil chemical and physical properties and plant nutrition (See Chapter 2). From plant elemental analysis we saw that barley, brome, and alfalfa grown on fly ash amended field plots had accumulated toxic concentrations of B in tissue, and yet the concentration of some beneficial nutrients was also increased. Soil pH was increased from slightly acidic, to neutral, to alkaline with an increase in fly ash rate. The fly ash was very saline, however, the soil/fly ash mixture was only slightly saline. The observed decrease in the Na:Ca ratio of the soil with fly ash application should improve soil physical properties by decreasing clay dispersion. A significant increase in soil bulk density and decrease in soil water content during dry periods was also measured.

Cereal crop yield is a product of three components: heads per unit area, kernel number per head, and individual kernel weight. To accurately identify the source of influence which fly ash may have on yield, the factors which may determine the size of each of these components must be understood. Tiller number per plant and fertile kernels per head at a given plant density are maximized by a high photosynthetic leaf area and a nonlimiting supply of nutrients (especially nitrogen) and water at early growth stages. However, an increase in plant density will decrease kernel number per head and tiller number per plant (Hay and Walker, 1989). Tiller survival is determined at intermediate stages of development and is dependent on levels of plant stress. Mean kernel weight is determined primarily by the quantity of photosynthates available for transport to the head between anthesis and maturity. Photosynthate availability depends upon green leaf area duration after anthesis and the photosynthetic activity of the ear, as well as source/sink relationships (Hay and Walker, 1989).

The objective of this two year field study was to determine the influence of fly ash from the Sundance power station at Highvale on growth and development of barley, brome, and alfalfa and subsequent influence on yield. If barley grain yield was influenced, the mechanism of fly ash influence would be determined by an evaluation of each yield component.

3.2 MATERIALS AND METHODS

3.2.1 Site Location And Experimental Design

Our study was conducted on reclaimed land at the Highvale coal mine owned by TransAlta Utilities Corporation. The mine is located at 53.5 °N, 114.6 °W, approximately 90 km west of Edmonton, Alberta, in the Mid Boreal Mixedwood ecoregion (Strong, 1992). Mean annual precipitation fo the site is 528 mm (Naeth and Chanasyk, 1993).

A randomized block design was employed in which one block was located in each of three reclaimed fields on the mine: Field 42, Field 43, and Field 45. There were six fly ash treatments (0, 25, 50, 100, 200, and 400 t/ha) and four vegetation treatments (no vegetation, barley (*Hordeum vulgare*, Jackson cv.), alfalfa (*Medicago sativa*, Beaver cv.), and smooth brome (*Bromus inermis*)) per block. The fly ash x vegetation treatments were randomly assigned totaling 24 plots in each block (Figure 2-1). The plot size was 16.6 m^2 (3.65 m x 4.55 m) with a buffer zone of 0.6 m between plots and a central corridor 3.5 m wide which separated two rows of 12 plots each.

Field 42 had been reclaimed in 1988 and Fields 43 and 45 were reclaimed in 1990. All fields had been revegetated with a forage mixture after approximately 150 cm of subsoil and 20 cm of topsoil had been replaced over the mine spoil. Subsoil and topsoil thickness may vary throughout each field. Topsoil and subsoil materials were comprised of a mixture of soil series from forest-grassland transitional Luvisolic and Solonetzic Soil Orders. These pre-disturbance soils developed on a complex distribution of saline and nonsaline glacial parent materials of varying textures derived from the Paskapoo and Edmonton geologic formations. The Edmonton formation was deposited in brackish water and subsequently soils which have developed on parent material derived from this formation often, but not always, have a high concentration of soluble sulfate salts. Thorsby, Kawood, Uncas, and Dnister are examples of soil series in the Highvale are which are derived from the Edmonton formation. The Paskapoo formation is primarily comprised of nonsaline sandstone and siltstone. The Modeste series is an example of a soil series in the Highvale mine area derived from the Paskapoo formation. As a result of soil variability, topsoil salvage included a high proportion of Solonetzic soils making these soils difficult to manage for reclamation. The topsoil in each field was a clay loam texture; the subsoil texture was clay to clay loam in Field 42, silty loam to clay loam in Field 43, and loamy sand to sandy loam in Field 45. From field observations during soil sampling, the properties (texture) of subsoil varied among plots in each field; topsoil properties were less variable.

3.2.2 Fly Ash Source And Application

Unweathered fly ash was taken from the Sundance power station on May 13 and 14, 1993. The coal source for the power station is described as sub-bituminous (A/B) coal from the Scollard member of the Tertiary and Upper Cretaceous Paskapoo geological formation. A sample of fly ash was sent to a commercial laboratory for total and water soluble elemental analysis. A known mass of fly ash was measured into a pail and spread on each plot on May 13 and 14, 1993; a rake was used to aid in spreading the low rate treatments. The fly ash was then incorporated to a depth of 10 to 15 cm by a single pass of a rototiller.

3.2.3 Soil Fertility And Seeding

Prior to seeding in 1993, for each field, one soil sample to 30 cm was taken from each of the 24 plots. For each rate of fly ash application at a given field, the four samples of that rate were combined. The six resulting samples from each field were sent to a commercial laboratory for routine soil fertility analysis and fertilizer recommendations.

The barley and alfalfa plots were seeded with a plot seeder (20- cm row spacing) on June 2, and the brome was hand broadcast on June 3, 1993. Barley was seeded at 100 kg/ha, brome at 9 kg/ha and alfalfa at 8 kg/ha. Prior to seeding, the barley was treated with Vitavax and the alfalfa was inoculated with *Rhizobium meliloti* (strain NRG185). Urea (0-46-0) and Triple Superphosphate (0-45-0) fertilizer was applied to barley and brome plots to provide 130 kg/ha of N and 30 kg/ha of P_2O_5. Alfalfa plots received 30 kg/ha N and 55 kg/ha of P_2O_5. Phosphorous was placed with seed (barley and alfalfa) and N was side banded.

In spring 1994, mine workers accidentally broadcast fertilized twelve plots in Field 42 and all plots in Field 45. The fertilizer was evenly distributed in Field 42 but unevenly distributed within plots of Field 45. The application rate was 50 kg/ha N and 18 kg/ha P_2O_5. In Field 42, the unfertilized alfalfa and brome plots were broadcast fertilized with an fertilizer rate equivalent to the accidental spreading. The brome plots in each field were subsequently fertilized to provide a total of 100 kg/ha N and 40 kg/ha P_2O_5. The alfalfa plots v… fertilized to provide a total of 40 kg/ha P_2O_5; no additional N was applied to the alfalfa. On May 24, 1994, the barley plots were again seeded with treated Jackson barley at a rate of 100 kg/ha. The plots were fertilized providing 25 kg/ha P_2O_5 with the seed and 100 kg/ha of N side banded. Fertilizer applied with barley during seeding was adjusted to compensate for the accidental fertilizer application described above.

3.2.4 Measurements Of Plant Health And Development

In 1993 and 1994 (barley) seedling emergence was measured using three 0.1 m^2 quadrates in each plot. Plant height, developmental stage, and symptoms of nutritional imbalance were monitored weekly in barley and every two to three weeks in alfalfa and brome.

3.2.5 Yield Determination

3.2.5.1 Barley

Three 0.1 m^2 samples were clipped at 5 cm above ground and grouped from each barley plot at 75 days (d) after seeding during 'soft dough' stage in 1993, and at boot stage (49d)and at soft dough stage (70 d) in 1994. After fresh and oven dry weights were determined the three replicate samples from each plot were combined. At barley maturation, 97 d in 1993 and 84 d in 1994, a plot clipper was used to cut a 6.4 m^2 area of barley from each plot. After drying the barley was threshed and the weights of straw and grain were recorded for yield calculation.

A sample of 100 kernels from the 1993 harvest was randomly selected from each treatment and weighed to determine individual kernel weight. In 1994, five plants in each treatment were marked for monitoring of plant development and symptoms. Plant development was recorded using the 'decimal code' system (Tottman et al., 1979). Leaf length, width (at later stages), and percentage necrosis was estimated on fully emerged, non-senesced leaves at stem elongation, head emergence, early milk, and soft dough stages. Percent necrosis was estimated by comparing to a standard leaf area chart. The main culm head from three of the five marked plants within each treatment was sampled to determine spikelet number, kernel number, and individual kernel weight. Herein, flag refers to the last emerged leaf, flag-1 to the first leaf directly below the flag leaf, and flag-2 to the leaf below flag-1. Barley scald disease and B toxicity was confirmed by a pathologist and a an agronomist at the Department of Agriculture, Food, and Rural Development of the Government of Alberta. Yield loss due to barley scald disease was predicted from the equation (Vaillancourt, 1994):

$$\text{yield loss} = \frac{((2/3 \times \%\ \text{flag necrosis}) + (1/2 \times \%\ \text{second leaf necrosis}))}{2}.$$

3.2.5.2 Alfalfa

At 97 d in 1993, two rows of alfalfa were cut at 5 cm above ground, weeds were removed, and samples weighed for yield. Stage of alfalfa development varied among fields; no treatment had reached the 10% flower stage. On June 22 and August 9, 1994, two 0.5 m^2 samples were cut from each treatment and weeds were removed. The combined weight (i.e. 1 m^2) of the two samples after oven drying (50 °C) was used for yield determination. The alfalfa was at 10% bloom on both sampling dates.

3.2.5.3 Brome

Due to uneven, patchy emergence, brome yield was not determined in 1993. On June 22, 1994, two 0.5 m^2 samples were cut and the weeds were separated. The samples and weeds were dried at 50 °C and the combined weight (i.e. 1 m^2) was used for yield analysis. The brome was in the anthesis stage of development.

3.2.6 Statistical Methods

Statistical analyses of the data for emergence and yield of barley, brome, and alfalfa, and leaf percent necrosis, length, and width and head component yield of barley, was determined using Fisher's Protected Least Significant Difference (FPLSD) (Steel and Torrie, 1980). Using FPLSD, a mean comparison (i.e. the LSD) can only be completed if the Probability > F (Prob>F) calculated from the ANOVA is ≤ 0.05.

3.3 RESULTS AND DISCUSSION

3.3.1 Barley

Fly ash treatments did not affect barley emergence significantly, perhaps because the reclaimed land was prepared for seeding during dry soil conditions resulting in large, dense, clayey aggregates and an unavoidably poor seed bed. The barley began to emerge at 5 to 6 d on all plots; the 0 t/ha treatment was slightly advanced compared with the fly ash amended treatments. Poor, uneven barley emergence on low fly ash treatments was attributed to poor soil-seed contact (Table 3-1). In fields 43 and 45 emergence was slightly greater for the 200 and 400 t/ha treatments compared with the lower rate treatments possibly related to improved seed-soil contact, however, in field 42 barley emergence decreased with increase in fly ash rate. Barley growth was delayed by 3 to 4 days on the 100, 200, and 400 t/ha plots compared to the 0 t/ha plot. Secondary emergence in low fly ash treatments occurred following a rainfall event at 20 to 22 d (Table 3-1). Better overall barley emergence in 1994 than in 1993 was attributed to superior seed bed and soil moisture conditions. Barley emergence was highest on the 0 and 25 t/ha treatments and lowest on the 400 t/ha treatment.

During and beyond soft dough stage in 1993 and 1994, the plots were disturbed either by flooding, pests (geese, birds), and/or disease, with the most severe problems occurring in Field 42. Barley development was increasingly delayed with increased fly ash rate to a maximum of 10 days. Initially, chlorosis and necrosis at the leaf tip and upper margins resulted in a white leaf tip covering <5% of the leaf area. Based on chemical analysis of barley tissue, we have attributed these early symptoms to marginal P deficiency. Dark brown necrotic spots developed first at leaf tip and margins and progressed toward the midrib and base eventually infecting the entire leaf blade and sheath. These symptoms were observed at early developmental stages and increasing severity with increase in fly ash rate and occurred on the oldest leaf first, eventually affecting all leaves. Similar symptoms were observed in 1993 and 1994. Based on the nature of these symptoms, chemical analysis of the barley, fly ash and soil, we have attributed the symptoms to B toxicity. In 1994, barley scald (*Rhynchosporium secalis*) infected all fly ash treatments but at earlier stages of development and increasing severity with decreasing fly ash rate. On many plants, infection was near the leaf collar affecting a small percentage of total leaf area but eliminating any transfer of photosynthate from the leaf and thus the overall influence was much greater. The overall influence of disease is considered in the descriptions below.

At stem elongation, toxicity symptoms were observed in the 100, 200, and 400 t/ha treatments (Table 3-2); barley scald had not yet developed. At head emergence, highest necrosis was observed for 0 and 25 t/ha although these symptoms were related to barley scald disease; lowest necrosis was observed in the 200 t/ha treatment (Table 3-3). Necrosis on the 400 t/ha treatment was also severe although primarily related to B toxicity and little occurrence of barley scald disease. Total necrosis at early milk stage was severe for all treatments but significantly less severe for the 200 t/ha treatment (Table 3-4). Barley scald was the primary source of necrosis in the 0, 25, 50, 100, and 200 t/ha treatments; boron toxicity was the source of necrosis for the 400 t/ha treatment. Disease related necrosis was significantly lower for the 200 and 400 t/ha treatments compared with other treatments. Increased barley scald resistance with increasing fly ash rate may be related to increased Ca concentration in plant tissue (Tewari et al., 1995), and, especially for the 400 t/ha treatment, a decreased available surface area for infection due to boron toxicity related necrosis. We observed a significant difference in flag-1 width and flag-2 length and width at head emergence stage (Table 3-3), and flag-1 width at early milk stage (Table 3-4). For each of these observations, the 200 t/ha treatment was highest in length and/or width, or, equal to the highest observation among treatments. From this we suggest that leaf area may have been highest for the 200 t/ha treatment, however, more accurate measurements are required to verify this observation. At soft dough stage all treatments were 100% necrotic/senesced primarily due to disease, and at high fly ash treatments, boron toxicity.

There was a significant difference in barley soft dough yield in both 1993, when 50 t/ha was highest, and 1994 when 200 t/ha was highest (Table 3-5). There was no significant difference in yield among fly ash treatments at boot stage, or in grain or straw. Grain yield was highest on the 50 t/ha treatment in 1993, and the 200 t/ha treatment in 1994; overall grain yield was lower in 1994 than 1993 (Table 3-5). Higher grain yield for the 200 t/ha treatment in 1994 is attributed to higher tiller number per plant (Table 3-6) and higher leaf photosynthetic area during grain filling stages (Tables 3-3 and 3-4). The overall decrease in emergence density (Table 3-1) with increase in fly ash rate may account for the increasing trend in tiller number (Table 3-6). Plant density trends do not, however, account for the low kernel number in the 400 t/ha which could then be related to boron toxicity or some other factor. The observed delay in development of the 400 t/ha treatment may actually have been a competition induced acceleration of plant development in the lower fly ash treatments (Hay and Walker, 1989). This, however, does not explain the slight delay of emergence in the 400 t/ha treatment. A delay would also result in a decrease in the duration of the grain filling stage resulting in lower kernel weight. Overall, lower grain yield in 1994 compared to 1993 is attributed to the decrease in individual kernel weight due to barley scald (Table 3-6). No statistically significant difference was observed among fly ash treatments for barley head components in 1994 (Table 3-6), however, kernel number per head, individual kernel weight, and total kernel weight were highest for the 100 t/ha treatment.

Grain yield loss due to barley scald disease can be predicted (Vaillancourt, 1994). By estimating and eliminating yield loss due to barley scald, fly ash dependent yield can be determined. In the absence of disease, the predicted total kernel weight per head would have been highest in the 100 t/ha treatment, and individual kernel weight would have been highest at 50 t/ha (Table 3-7). Since the disease affects total photosynthate production during kernel filling stage, not kernel number per head, total kernel weight per head should provide a more accurate prediction of fly ash dependent yield. Overall grain yield cannot be predicted without accounting for the number of heads per unit area and kernel number per head including tillers. These observations were not made.

The barley was harvested 13 days earlier in 1994 than 1993 probably due to warm dry weather in August 1994 compared with cool, wet weather in August of 1993. Premature senescence of the flag and lower leaves due to barley scald in 1994 may also have contributed to the early maturation. There was only a five day difference in sample time at the soft dough stage.

3.3.2 Alfalfa

There were no significant differences in alfalfa emergence among fly ash treatments (Table 3-1). Alfalfa began to emerge in patches between 9 and 14 d and continued during the following two weeks. Emergence on the 400 t/ha treatment was delayed compared with the other treatments. At 14 d, alfalfa plants in the 0 t/ha treatment were entering the 2-leaf stage compared to the 1-leaf stage on the 400 t/ha treatment; delay in development increased with increased fly ash rate. At 33 d, alfalfa establishment was visibly suppressed in the 400 t/ha treatment. The cotyledon emerged but development progressed very slowly and the cotyledon became chlorotic. At 40 d, necrosis was evident at the tips and margins of older leaflets of advanced plants on the 400 t/ha treatment. Very few alfalfa plants became established on the 400 t/ha treatment. Once established, no symptoms were evident except necrosis and premature senescence of the oldest few leaves. Although the alfalfa has a high B requirement and can tolerate a moderately high B concentration in tissue, in the 400 t/ha treatment, B concentration may have exceeded tolerable levels at the sensitive seedling stage of development. Once established, tolerance would have increased, and alfalfa rooting depth would have exceeded the depth of the fly ash amended layer. All alfalfa plots suffered some herbicide stress in 1994 ranging from 15% chlorosis in Field 42 to <5% in Field 45; the plants seemed to recover fully.

No significant difference was observed in yield among treatments in 1993. Yield of the 400 t/ha treatment in the first 1994 cut was significantly lower than all other treatments among which there was no significant difference (Table 3-5). Yield of the 200 t/ha treatment in the second 1994 cut was significantly higher than the other treatments among which there was no significant difference. The source of yield differences is difficult to determine, however, benefits may result from increased soil pH and nutrient availability (see Chapter 2). Poor establishment in the 400 t/ha treatment may be related to the slight increase in soil salt content or elemental toxicity at seedling stage.

3.3.3 Brome

Brome emergence began 55 days after seeding. Emergence was uneven on all plots but lowest for the 400 t/ha treatment. Plants in all fly ash treatments initially had an unusual and unexplained prostrate growth habit. Some brome plants were just beginning to enter the heading stage at 97 d when overnight frost was becoming frequent. No symptoms of nutrient imbalance were apparent on the brome in 1993. Up to 30% necrosis was observed on brome plants in the 400 t/ha treatment in 1994. The nature of the symptoms (boron toxicity) was similar to but not as severe as in barley. No significant difference in yield among treatments was observed although yield of fly ash amended treatments all exceeded that of the 0 t/ha treatment. Compared with alfalfa, the rooting depth of both brome and barley is much shallower and would thus have had greater exposure to the influence of fly ash.

3.4 CONCLUSIONS

Complex interactions of environmental conditions, soil variability, agronomic conditions and practices, pests and plant diseases contributed to few significant treatment differences. However, some general interpretations can be made: the 400 t/ha treatment never produced a positive yield result indicating that this rate was excessive. Intermediate fly ash treatments (50, 100, and 200) produced the largest yield increase. The optimum rate of fly ash application for crop yield ranged between 100 and 200 t/ha. Long term yield evaluation on various soils is required to determine optimum rates. Boron toxicity on the 200 and 400 t/ha treatments may influence the determination of kernel number per head at early growth stages, tiller survival at intermediate growth stages, and total kernel weight per head during kernel filling stages. Fly ash increased barley resistance to barley scald disease; the source of resistance could not be determined in this study but may be related to an increase in Ca concentration with fly ash rate. These observations may be of further interest to crop pathologists.

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Table 3-1. Mean emergence of barley, alfalfa, and brome at specified days after seeding.

Fly Ash (t/ha)	Barley 1993 9 days	Barley 1993 23 days	Barley 1994 13 days	Alfalfa 1993 40 days	Brome 1993 62 days
0	9.6	13.0	24.3	12.0	8.0
25	9.0	11.6	24.3	18.0	12.0
50	7.0	8.6	21.0	12.6	9.0
100	10.6	11.6	22.0	7.0	10.3
200	14.0	15.0	21.0	11.0	7.6
400	14.6	15.0	18.6	3.6	5.0
Prob>F	0.84	0.84	0.20	0.32	0.90

Table 3-2. Mean barley leaf necrosis and length at stem elongation stage, 1994.[†]

Fly Ash	Total Nec[illegible]				Length (cm)			
(t/ha)	Leaf 1	Leaf 2	L[illegible]	[illegible]	Leaf 1	Leaf 2	Leaf 3	Leaf 4
0	0 c	0 b	[illegible]	[illegible] a	9 ab	13	15	16
25	0 c	0 b	[illegible]	[illegible] a	9 ab	14	16	16
50	0 c	0 b	0	0 a	8 [illegible]	13	15	15
100	6 c	1 b	0	0 a	10 a	14	15	15
200	18 b	4 b	1	0 a	10 a	14	16	15
400	42 a	18 a	6	4 a	8 b	13	10	7
Prob>F	0.00	0.00	0.23	0.00	0.05	0.58	0.10	0.11

[†] Means within a column followed by the same letter are not significantly different (α=0.05).

Table 3-3. Mean barley leaf total necrosis, length, width, and disease related necrosis at head emergence stage, 1994.[+]

Fly Ash (t/ha)	Total Necrosis (%)			Disease Necrosis (%)		
	Flag	Flag-1[‡]	Flag-2[§]	Flag	Flag-1	Flag-2
0	33	77	93 a	33 a	77 a	92 a
25	16	60	79 ab	16 ab	60 ab	62 ab
50	7	37	79 ab	7 b	35 bcd	53 bc
100	7	39	55 bc	6 b	38 bc	53 bc
200	7	25	33 c	3 b	20 cd	25 cd
400	20	53	56 abc	0 b	12 d	13 d
Prob>F	0.13	0.13	0.05	0.02	0.00	0.00

Fly Ash (t/ha)	Length (cm)			Width (mm)		
	Flag	Flag-1	Flag-2	Flag	Flag-1	Flag-2
0	18	24	24 a	18	15 c	10 c
25	16	22	23 a	16	15 bc	10 c
50	18	24	24 a	18	18 ab	12 bc
100	18	24	25 a	18	18 a	14 ab
200	17	25	25 a	18	19 a	16 a
400	17	22	21 b	19	20 a	15 a
Prob>F	0.94	0.39	0.02	0.37	0.01	0.01

[+] Means within a column followed by the same letter are not significantly different (α=0.05)
[‡] Leaf directly below flag leaf
[§] Second leaf directly below flag leaf

Table 3-4. Mean barley leaf total necrosis, length, width and disease related necrosis at early milk stage, 1994.[+]

Fly Ash (t/ha)	Total Necrosis (%)		Disease Necrosis (%)		Length (cm)		Width (mm)	
	Flag	Flag-1[‡]	Flag	Flag-1	Flag	Flag-1	Flag	Flag-1
0	88 a	99	91 a	85	18	24	16	14 b
25	90 a	97	90 a	97	16	22	15	13 b
50	92 a	99	96 a	96	18	24	17	14 b
100	58 ab	97	57 b	96	17	24	17	16 ab
200	31 b	83	24 c	79	17	25	18	17 a
400	71 ab	88	13 c	45	18	22	17	17 a
Prob>F	0.04	0.18	0.00	0.07	0.95	0.29	0.60	0.01

[+] Means within a column followed by the same letter are not significantly different (α=0.05)
[‡] Leaf directly below flag leaf

Table 3-5. Mean yield (t/ha) of crops on fly ash amended plots.⁺

Fly Ash (t/ha)	Barley 1993 soft dough	Barley 1993 grain	Barley 1993 straw	Barley 1994 boot	Barley 1994 soft dough	Barley 1994 grain	Barley 1994 straw	Alfalfa 1993	Alfalfa 1994 cut 1	Alfalfa 1994 cut 2	Brome 1994
0	8.9 abc	2.8	2.2	2.9	6.3 b	1.1	2.1	0.9	3.1 a	2.2 b	3.2
25	8.3 bc	3.1	2.4	3.9	6.9 b	1.5	2.6	1.9	3.3 a	2.5 ab	4.6
50	10.9 a	3.3	2.6	5.4	7.6 ab	1.4	2.3	1.3	3.1 a	2.4 ab	4.1
100	9.0 ab	2.9	2.3	3.8	7.0 b	1.4	2.6	1.3	3.2 a	2.2 b	4.9
200	6.9 cd	2.7	2.2	4.4	9.2 a	1.6	2.7	0.9	3.6 a	3.1 a	4.4
400	5.8 d	1.8	1.4	3.1	5.8 b	1.4	2.5	0.4	1.6 b	1.9 b	3.4
Prob>F	0.01	0.47	0.46	0.19	0.01	0.32	0.79	0.21	0.04	0.05	0.56

⁺ Means within a column followed by the same letter are not significantly different (α=0.05)

Table 3-6. Mean yield of barley head components.⁺

Fly Ash (t/ha)	tiller number per plant	spikelet number per head	total head weight (g)	kernel number per head	total kernel weight (g/head)	1994 kernel weight (g/100 kernels)	1993 kernel weight‡ (g/100 kernels)
0	1.0	20	1.69	62	1.45	2.3	3.7
25	1.1	20	1.48	57	1.23	2.1	3.7
50	0.9	20	1.60	56	1.35	2.4	3.7
100	1.3	22	2.05	62	1.74	2.8	3.9
200	1.8	20	1.65	60	1.43	2.4	3.9
400	1.6	20	1.37	54	1.13	2.1	3.4
Prob>F	0.30	0.21	0.23	0.14	0.23	0.47	0.74

⁺ resutls from 1994 unless otherwise stated
‡ mean weight of 100 randomly chosen kernels sampled in 1993

Table 3-7. Predicted 1994 barley kernel yield without necrosis due to boron (B) toxicity and disease.

Fly Ash	Predicted Yield Loss[‡]		Predicted Yield Without Disease (B toxicity only)	
	B toxicity and disease	disease only	kernel weight	total kernel weight
t/ha	%	%	(g/100 kernels)	(g/head)
0	54	51	4.8	2.97
25	54	54	4.6	2.70
50	55	55	5.3	2.97
100	44	43	4.9	3.05
200	31	28	3.3	1.98
400	46	16	0.024	1.34

[‡] Yield loss due to necrosis = ((2/3 x % flag necrosis) + (1/2 x %second leaf necrosis)) /2 (Vaillancourt, 1994)

4. TEMPERATURE REGIMES OF FLY ASH AMENDED SOILS

4.1 INTRODUCTION

The potential of fly ash, a waste by-product of coal combustion, as a soil amendment is currently being evaluated globally. Its potential benefits include improving soil texture and water holding capacity, increasing soil pH, and enhancing soil fertility (Carlson and Adriano, 1993). Several researchers have indicated, with reference to Adriano et al. (1980), that the application of fly ash as a soil amendment will result in an increase in soil temperature (Sharma et al., 1989; Carlson and Adriano, 1993). However, no clear scientific evidence has been provided to support this hypothesis.

The influence of fly ash on soil temperature is of importance, especially in arid regions where fly ash may improve soil temperature due to change in texture and in northern regions which have a short growing season. An increase in rate of soil warming in spring would be an additional benefit of fly ash as a soil amendment. Higher spring soil temperatures could lengthen the growing season and/or increase germination percentage and rate (Hegarty, 1973).

The altered physical properties of fly ash amended soils may change the soil temperature regime by influencing absorbance of radiation, thermal conductivity, and heat capacity of the soil. These physical properties include soil color, bulk density, and water content. The surface application of fly ash would most likely increase reflectance of solar radiation from the soil surface and would thus decrease absorbance of radiation and suppress soil warming. With the addition of silt sized fly ash, Chang et al. (1977) measured a decrease in bulk density on coarser textured soils and an increase in bulk density of a finer textured soil. They also measured a change in soil water content with the addition of fly ash. Bulk density and water content determine the volume of soil which is occupied by air; air has a much lower thermal conductivity and heat capacity than water and minerals (Hillel, 1982). Presumably, the magnitude of influence on soil physical properties would depend on initial soil texture and organic matter content and the amount and depth of fly ash amendment (Chang et al., 1977).

The objective of this study was to quantify the influence of the field application of fly ash on the temperature of a reclaimed soil.

4.2 MATERIALS AND METHODS

4.2.1 Site Description and Project Design

This research was conducted at the Highvale surface coal mine owned by TransAlta Utilities Corporation. The site is located in the Mid Boreal Mixedwood ecoregion at 53.5°N, 114.6°W; approximately 90 km west of Edmonton, Alberta. Mean annual precipitation of the region is 528 mm (Naeth and Chanasyk, 1993). A sub-bituminous coal is the source for the Sundance power station at the Highvale coal mine.

The research was conducted in conjunction with an evaluation of plant yield and elemental uptake on fly ash amended plots. A randomized block design was employed in which one block was located in each of three reclaimed fields on the mine: Fields 42, 43, and 45. The design includes six fly ash rates (0, 25, 50, 100, 200, and 400 t/ha) and four vegetation treatments (control; barley (*Hordeum vulgare* L.); alfalfa (*Medicago sativa* L.); and smooth brome (*Bromus inermis* Leyss.)) per plot. Plot size was 16.6 m^2 (3.65 m x 4.55 m); a buffer zone of 0.6 m was left between plots. A central corridor 3.5 m wide separated two rows of 12 plots each.

The study sites had been revegetated with a forage mixture after approximately 150 cm of subsoil and 20 cm of topsoil had been replaced over the mine spoil in either 1989 or 1990. The topsoil in each field was a clay loam texture while the subsoil was clay to clay loam in Field 42, silty loam to clay loam in Field 43, and loamy sand to sandy loam in Field 45. Since the topsoil and subsoil in each field were a mixture of several soil series (Hartley, 1994, TransAlta Utilities Corporation, personal communication), soil properties likely varied among and within plots of each field.

4.2.2 Plot Development

A selected area in each field was disked and cultivated prior to fly ash application. Fly ash density was determined and the volume of ash needed for each rate treatment was calculated. The fly ash was measured into pails and spread each plot at the desired rate; a rake was used to aid in spreading the low rate treatments. The fly ash was then incorporated to a depth of 10-15 cm with a single pass of a rototiller. The vegetation treatments were seeded, harrowed and packed on June 2, 1993 immediately after plot establishment and fly ash application. The pH of the fly ash was 12.0.

On June 4, 1993, a nest of thermistors was installed in each of the 0, 100, 200, and 400 t/ha fly ash treatments of the barley, alfalfa, and control treatments. Thermistors were placed at depths of 5, 10, and 20 cm. To avoid a vegetation x fly ash interaction and to account for variability within each plot, thermistors from barley and alfalfa treatments were removed in April 1994 and were placed in the control vegetation treatment. As a result, there were a total of three thermistor nests in each of the 0, 100, 200, and 400 t/ha treatments of the control vegetation treatment at depths of 5, 10, and 20 cm.

4.2.3 Measurements

Thermistor readings were taken at several times throughout summer 1993 and 1994 using a hand held resistance meter. A manufacturer's calibration, previously tested by the authors, was used to convert resistance to temperature. Diurnal readings were taken every two hours for a 24 hour period beginning at 0800 h MST on June 17 and 18, 1993 and July 28 and 29, 1994. On July 15, 1993, soil temperature readings were taken every two hours between 0600 h and 2400 h. Readings were also taken between 1400 h and 1600 h in spring 1994 on May 10, May 25, May 30, and June 3. These summer and spring measurements were chosen as representatives of the overall influence of fly ash. The barley and alfalfa vegetation which had just started to emerge at the time of the June 1993 readings were assumed to have had negligible influence on soil temperature. At the end of the study, all thermistors were removed and standardized using water baths at several temperatures.

Soil moisture and bulk density (Db) measurements to a 7.5 cm depth were taken with a surface moisture/density probe. The measurements were taken in conjunction with the June and July 1993 and July 1994 thermistor readings. Three moisture/density readings were taken approximately 0.5 m from each of the thermistor nests within each plot and averaged. All observations were made following several weeks of dry weather.

The depth of soil sampling for particle size analysis was adjusted to the depth of fly ash incorporation which varied from 10 to 15 cm among plots. Analysis of these samples was conducted using the hydrometer method (McKeague, 1978).

4.2.4 Maintenance

Plots with crops were hand weeded throughout the summer 1993. The control was hand weeded in early summer, and rototilled once in August and once in September. In 1994, the control plots were treated with glyphosate herbicide or clipped for weed control. The plots had not been disturbed for approximately 10 months at the time of the summer temperature measurements; disturbance was minimized during thermistor installations in spring 1994.

4.2.5 Statistical Analysis

Mean bi-hourly temperature was determined for each treatment. Mean daily (average of all readings taken), maximum and minimum temperatures, and amplitude above and below the daily mean were determined for each treatment from the mean bi-hourly observations in June 1993 and July 1994. Due to an incomplete data set, mean daily temperature for July 1993 was calculated by adding 1/2 of the difference between daily maximum and minimum to the daily minimum temperature. Statistical significance was determined using Fisher's Protected Least Significant Difference (FPLSD) (Steel and Torrie, 1980). Using FPLSD, a mean comparison (i.e. the LSD) can only be completed if the Probability > F (Prob>F) calculated from the ANOVA is ≤ 0.05. These statistical analyses were also conducted for the soil water and bulk density data.

4.3 RESULTS

4.3.1 Particle Size Analysis

The particle size analysis of the fly ash amended soils and pure fly ash is shown in Table 4-1. The clay contents of the 200 and 400 t/ha treatments were significantly lower than those of the other treatments. The silt content of the 400 t/ha treatment was significantly higher than that of the 0 and 100 t/ha treatments. The percentage sand among treatments was not significantly different. None of the particle size fractions for the 0 and 100 t/ha treatments were significantly different. Despite the observed significant differences among rates which were observed, the control and all of the fly ash amended soils would be described as clay loam in texture (Agriculture Canada Expert Committee on Soil Survey, 1987).

4.3.2 Surface Moisture And Color

The volumetric moisture content (VMC) of the amended treatments decreased with fly ash rate on each observation date (Table 4-2). On July 28, 1994, the VMC of the fly ash amended plots was significantly decreased with increased fly ash rate ranging from 16% for the 0 t/ha treatment to 8% for the 400 t/ha treatment. The lower moisture content of the soils with the higher fly ash treatments may be related to their lower clay content or the influence of fly ash on downward percolation of water and on aeration. VMC of the 100, 200, and 400 t/ha treatments were lower than that of the control by approximately 13, 26, and 50% (relative), respectively. There was a significant difference between the 0 t/ha treatment and the 100, 200, and 400 t/ha treatments on all three observation dates.

The color of the ash amended soil was not quantified but was observably lighter (i.e. had a higher value and lower chroma) than the unamended soil.

4.3.3 Surface Bulk Density

There was no significant difference in Db among fly ash treatments on June 17, 1993 (Table 4-2) although a trend to increasing Db with increased fly ash is evident. In

July of 1993 and 1994, Db was lower in the 0 t/ha treatment than in both the 200 and 400 t/ha treatments. On July 28, 1994, the Db of the fly ash amended plots increased with increased fly ash rate, with Db ranging from 1.10 Mg/m^3 (0 t/ha treatment) to 1.22 Mg/m^3 (400 t/ha treatment). We observed smaller, more friable aggregates in the fly ash amended plots which can be attributed to the spherical glassy nature of the fly ash particles. This, in conjunction with the lower clay content reduced the shrink swell capacity of the soil which was exemplified by the notable absence of cracks in the soil at the 200 and 400 t/ha treatments. On this date Db in Field 42 for the 0 t/ha rate ranged from 0.98 to 1.14 Mg/m^3 and the 400 t/ha treatment ranged in Db from 1.12 to 1.23 Mg/m^3 within the plot.

4.3.4 Diurnal Temperature Measurements

As shown in Tables 4-1 to 4-7 and Figure 4-1, fly ash had a significant influence on soil texture, moisture, bulk density, and temperature. The extent of influence will be described in the sections which follow. Examples of diurnal soil temperature curves are provided in Figures 6-1 to 6-3 of Appendix 6.3. The average length of time to complete a single set of soil temperature observations was approximately 35 minutes. Soil temperature change over a 30 minute period is illustrated by Figure 6-4.

4.3.4.1 1993 Measurements

Based on hourly measurements, the mean air temperature for June 17 to 18 was 17.9 °C. Air temperature reached a maximum of 23.3 °C at 1500 h on June 17 and a minimum of 14.2 °C on June 18. Due to erratic early morning (0600 h to 0800 h) data, mean daily air temperature for July 15 could not be calculated. On July 15, air temperature reached a maximum of 19.9 °C at 1300 h and a minimum of 1[illegible].5 °C at 2300 h. Midnight temperature was not available.

Soil temperature for June 1993 decreased linearly with depth (Fig. 4-1a). At the 5-cm depth, daily mean temperature was significantly higher in the 200 t/ha treatment than in all other treatments (Table 4-3). At the 20-cm depth, there was no difference between the daily means of the 0 and 200 t/ha treatments which were significantly higher than the means for the 400 and 100 t/ha rates. At the 5-cm depth, the amplitudes of diurnal temperature fluctuations were greater for the 200 and 400 t/ha treatments than the 0 t/ha treatment, but this difference diminished with depth. There was no difference between the amplitudes of the temperature fluctuations for the 0 and 100 t/ha treatments.

On July 15, none of treatment means, maximums, nor amplitudes were significantly different at any depth (Table 4-4). The mean temperature of the 400 t/ha treatment was 1.1 °C lower than that in the 0 t/ha treatment at the 5-cm depth, 1.0 °C lower at the 10-cm depth, and 1.2 °C lower at the 20-cm depth (Figure 4-1b). The minimum temperature of the 400 t/ha treatment was significantly lower than that of the 0 t/ha treatment at only the 5-cm depth. There was no noticeable shift in phase.

4.3.4.2 1994 Measurements

Air temperature data for the spring 1994 set of observations are shown in Table 4-5. During the July 27 to 28 observation period, air temperature had a mean of 20.2 °C, maximum of 27.3 °C, and minimum of 13.6 °C (time of max. and min. were unavailable). There was no measurable precipitation in the area for two weeks prior to the observations.

In spring 1994, there were no significant differences in soil temperature among treatments at the 5- nor 10-cm depths on any date (Table 4-6). This may be related to the time (i.e. hour) of observation. At the 20-cm depth on each spring date, temperatures decreased progressively with increased rate of fly ash application. The temperature difference at 20 cm between the 0 and 400 t/ha treatments ranged from 0.8 °C on May 10 to 1.6 °C on May 25.

Soil temperature trends with depth in July 1994 (Figure 4-1c) were comparable to those observed for July 1993 (Figure 4-1b). In July 1993 and 1994, soil temperatures at all three depths of measurement were highest in the 0 t/ha treatment and lowest in the 400 t/ha treatment (Figure 1). Differences between the 100 and 200 t/ha treatments were small.

In July 1994, there were no significant differences in mean daily temperature among treatments (Table 4-7). The mean temperature of the 400 t/ha treatment at the 10-cm depth was 0.9 °C lower than that of the 0 t/ha treatment and 1.2 °C lower at the 20-cm depth. Maximum and minimum temperatures of the 0 t/ha treatment were higher than those for the 100, 200, and 400 t/ha treatment at all depths although differences were not always significant. The above mean temperature amplitudes of the 0 t/ha treatments were lower than those of the 400 t/ha treatments at the 5-cm depth but were higher at the 20-cm depth while the opposite trend was observed for the amplitude below the mean. No treatment-related phase shift was observed.

4.4 DISCUSSION

Fly ash amendment of the soil concerned had some specific meaningful effects on soil texture, bulk density, moisture content and temperature to a 20-cm depth (Tables 4-1 to 4-7 and Figure 4-1).

The increase in proportion of silt and decrease in the proportion of clay in the fly ash amended topsoils compared with the unamended topsoil was related to the proportions of silt and clay in the fly ash. The measured decrease in soil moisture supports the results of Watson (1994) who found soil moisture retention decreased as the proportion of fly ash added to a silty clay soil increased.

The conflicting reports regarding the influence of fly ash on soil Db have been summarized by Sharma et al. (1989). Where initial soil Db was >1.25 Mg/m^3, Db decreased with the addition of fly ash. However, Db increased with the addition of fly ash to soils with an initial Db between 0.89 and 1.01 Mg/m^3. Considering our soil had a Db between 1.04 and 1.11 Mg/m^3, an increase in Db by the addition of fly ash might be expected. These trends in Db are likely related to the difference in texture between treatments. Soil texture differences among treatments was the probable source of trends in Db.

The June 1993 soil temperature trends, particularly of the 200 t/ha treatment, were not consistent with those from July 1993 and 1994 (Figure 4-1). The June 1993 observations were made less than three weeks after fly ash application and thermistor installation. Thus, trends in this set of observations represent a soil which may not have completely settled after fly ash application. There was sufficient time and rain for soil settling to occur by July 1993 and July 1994 (following fall tillage).

The addition of fly ash decreased the efficiency of heat transfer through the soil and subsequent warming at 20 cm as evidenced by the smaller difference between mean temperature of the 5- and 20-cm depths of the 0 t/ha treatments compared with the fly ash amended treatments (Tables 4-3 to 4-7). These trends could be related to depth of fly ash incorporation or increased soil porosity. Reasonable evidence is provided from the results from July 1993, Spring 1994, and July 1994 to conclude that soil temperature decreased with fly ash treatments in excess of 100 t/ha. These interpretations do not support the trends reported by Carlson and Adriano (1993).

The primary factors influencing soil thermal properties are Db and moisture (Hillel, 1982). Sepaskhah and Boersma (1979) determined that soil water content is the primary factor affecting thermal conductivity. They found that at low water contents, thermal conductivity remained relatively constant up to a critical point. Beyond this point thermal conductivity increased rapidly as soil water increased eventually reaching a maximum. Soil clay content was the primary factor determining the critical water content beyond which thermal conductivity increased. Based on figures provided by Sepaskah and Boersma (1979) and our soil texture data, only the 0 t/ha treatment of July 1993 may have reached the critical water content beyond which thermal conductivity was increased. Differences in thermal conductivity among other treatments in our study would be small. Without intensive measurements, it is difficult to assess if a small water related difference in thermal conductivity would account for the observed temperature differences.

Assuming negligible differences in soil moisture, an increase in Db would be expected to increase thermal conductivity due to reduced soil porosity and better particle-to-particle contact. The net result of fly ash addition should therefore be wider temperature fluctuations and higher temperatures at depth. Any fly ash related change in thermal conductivity would affect both soil warming and soil cooling.

Soil color may also have had a significant influence on soil temperature trends. Lighter colored soils tend to have greater reflection of radiation from the soil surface. Thus it can be assumed that the net amount of radiation absorbed by the soil was smaller for the ash amended treatments. Soil temperature should be lower on plots which have been amended with enough fly ash to change surface color.

Soil surface cracking may also influence soil temperature by increasing soil surface area exposed to radiation and increasing water evaporation from the soil. Soil surface cracking during dry weather was predominantly restricted to the 0 t/ha treatments and, to a smaller extent, the 100 t/ha treatments. Decreased aggregate stability would contribute to a reduction in soil cracking. The decreased aggregate stability of fly ash amended soils, measured by modulus of rupture, is well documented (Watson, 1994; Sharma et al., 1989). The lower clay content combined with decreased aggregate stability would account for the absence of cracks especially in the 400 and 200 t/ha treatments. Increased cracking should have increased evaporation from the soil which should have lowered both soil temperature and water content. Since soil temperature and moisture content was higher for the 0 t/ha treatment, these effects must have been negligible.

The overall decrease in soil temperature with the addition of fly ash is most likely the net result of the many influences fly ash has on the physical properties of the soil. At this latitude, the agronomic influence of soil temperature on plant growth would be greatest during spring warming when heat is needed to enhance germination and seedling establishment. During this period, no significant difference in soil temperature was observed at the 5-cm depth which is the layer most critical for plant germination. The largest difference, (1.1 °C), between the 0 and 400 t/ha treatments observed at a 20-cm depth on May 30, is not likely sufficient to be biologically significant to seed germination (Hegarty, 1973).

4.5 CONCLUSIONS

Under dry conditions, on a fine textured soil, fly ash amendment in excess of 100 t/ha may decrease soil temperature. However, the magnitude of this decrease is likely of limited biological consequence.

Generalizations made in review papers (e.g. Carlson and Adriano, 1993; Sharma et al., 1989; El-Mogazi et al., 1988; Adriano et al., 1980) regarding the influence of fly ash on soil temperature, bulk density, and water holding capacity must be considered with caution since many are based on coarse to medium textured soils. Further research on fine textured soils is needed.

4.6 REFERENCES

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Table 4-1. Particle size analysis of fly ash amended soils.+

Ash Rate (t/ha)	Mean Size Fractions clay (%)	silt (%)	sand (%)
0	38 a	40 ab	22
100	36 a	39 ab	24
200	31 b	43 bc	27
400	29 b	47 c	24
Prob >F	0.01	0.01	0.61
pure ash	13	55	32

+ Means within each column followed by the same letter are not significantly different (α= 0.05)

Table 4-2. Mean surface (0-7.5 cm) volumetric water content and bulk density of fly ash amended plots on selected dates.+

Rate (t/ha)	Volumetric Water Content (%)			Bulk Density (Mg/m3)		
	June'93	July'93	July'94	June'93	July'93	July'94
0	20.7 a	27.5 a	16.3 a	1.11	1.04 c	1.11 c
100	16.4 b	20.3 b	13.9 b	1.12	1.08 bc	1.15 bc
200	15.9 b	20.0 bc	10.8 c	1.12	1.11 ab	1.19 ab
400	13.0 c	16.5 c	7.8 d	1.15	1.14 a	1.22 a
Prob >F	0.02	0.00	0.00	0.31	0.02	0.01

+ Means within a column followed by the same letter are not significantly different(α = 0.05)

Table 4-3. Statistical summary of diurnal soil temperature parameters (°C) of fly ash amended treatments, June 17 to 18, 1993 (0800 h-0800 h). †

Rate (t/ha)	Mean	Max	Min	Amp + ‡	Amp - §
5-cm depth					
0	20.5 b	24.5 b	17.0 a	3.0 b	3.5 b
100	20.4 b	23.4 b	16.9 a	2.8 b	3.5 b
200	20.9 a	24.6 a	17.1 a	3.7 a	3.8 a
400	20.5 b	24.4 a	16.6 b	3.8 a	4.0 a
Prob > F	0.00	0.00	0.00	0.00	0.00
10-cm depth					
0	19.8 b	21.8 bc	17.1 a	2.0 b	2.7 a
100	19.6 b	21.6 c	17.0 a	1.9 b	2.6 a
200	20.2 a	22.6 a	17.1 a	2.4 a	3.1 b
400	19.7 b	22.2 ab	16.6 b	2.5 a	3.1 b
Prob > F	0.00	0.00	0.00	0.00	0.00
20-cm depth					
0	18.6 a	19.7 a	17.3 a	1.1	1.3 a
100	18.3 b	19.5 ab	17.0 b	1.2	1.3 a
200	18.7 a	19.8 a	17.2 ab	1.1	1.5 b
400	18.1 b	19.1 b	16.7 c	1.1	1.3 a
Prob > F	0.00	0.00	0.00	0.77	0.00

† At each depth, means within a column followed by the same letter are not significantly different ($\alpha = 0.05$); observations were made at 2 hour intervals over a 24 hour period

‡ Amp+ amplitude above the mean

§ Amp- amplitude below the mean

Table 4-4. Statistical summary of soil temperature parameters (°C) of fly ash amended treatments on July 15, 1993 (0600 h-2400 h)

Rate (t/ha)	Mean	Max	Min	Amplitude
5-cm depth				
	19.4	23.7	15.2 a	4.2
	19.1	23.3	14.9 a	4.2
200	19.0	22.9	14.0 ab	5.0
400	18.3	23.6	13.0 b	5.3
Prob >F	0.29	0.96	0.02	0.42
10-cm depth				
0	19.0	21.7	16.3	2.7
100	18.6	[illegible]	1[illegible].9	2.7
200	18.6	[illegible].8	15.5	3.1
400	18.[illegible]	[illegible]	14.6	3.4
Prob >F	0.45	0.68	0.12	0.17
20-cm depth				
0	18.4	19.7	17.2	1.2
100	18.0	19.2	16.9	1.2
200	18.0	19.3	16.6	1.4
400	17.2	18.5	16.0	1.[illegible]
Prob >F	0.10	0.18	0.06	0.52

[†] At each depth, means within a column followed by the same letter are not significantly different (α = 0.05)

Table 4-5. Daily air temperature measurements for the spring 1994 observations

Date (1994)	Mean Air Temp (°C)	Max. Air Temp (Time) (°C)	Min. Air Temp (Time) (°C)
May 10	15.1	20.4 (1500h)	9.9 (0500h)
May 25	16.8	25.7 (1500h)	7.4 (0300h)
May 30	12.0	18.7 (1500h)	4.3 (2400h)
June 3	14.9	22.3 (1700h)	3.0 (0500h)

Table 4-6. Mean soil temperature of fly ash amended treatments taken between 1300 h and 1500 h on May 10, May 25, May 30, and June 3, 1994. [+]

Rate (t/ha)	10-May	25-May	30-May	3-June
5-cm depth				
0	18.8	22.8	20.2	22.4
100	18.9	22.3	19.7	22.1
200	18.9	22.6	20.3	22.5
400	19.7	22.3	20.8	23.0
Prob >F	0.29	0.96	0.58	0.81
10- cm depth				
0	15.8	19.0	16.9	18.4
100	15.1	17.7	16.1	17.4
200	15.3	18.0	16.5	17.9
400	15.7	17.7	16.9	18.2
Prob >F	0.45	0.26	0.20	0.29
20- cm depth				
0	12.8 a	14.7 a	14.0 a	14.6 a
100	12.4 ab	13.6 b	[illegible] b	14.1 b
200	12.4 ab	13.5 b	13.3 b	14.1 b
400	12.0 b	12.9 c	12.9 c	13.7 c
Prob >F	0.05	0.00	0.00	0.00

[+] At each depth, means within a column followed by the same letter are not significantly different ($\alpha = 0.05$)

Table 4-7. Statistical summary of diurnal soil temperature parameters of fly ash amended treatments, July 28 to 29, 1994 (0800 h-0800 h). [+]

Rate (t/ha)	Mean	Max	Min	Amp + [‡]	Amp- [§]
5-cm depth					
0	24.4	29.7	18.9 a	5.1	6.0
100	23.9	29.3	18.6 b	5.3	5.7
200	23.9	29.5	18.2 c	5.5	5.6
400	23.7	29.4	17.7 d	5.7	5.3
Prob >F	0.27	0.86	0.00	0.13	0.31
10- cm depth					
0	23.5	27.2	20.1	3.6	3.4 a
100	22.9	26.2	20.0	3.3	2.9 b
200	22	26.1	19.7	3.4	3.1 ab
400	22.6	26.3	19.2	3.7	3.3 a
Prob >F	0.09	0.09	0.13	0.14	0.04
20- cm depth					
0	22.3	23.9 a	21.0	1.3	1.3
100	21.7	23.1 ab	20.5	1.4	1.2
200	21.7	23.3 ab	20.6	1.6	1.1
400	21.1	22.4 b	20.1	1.2	1.0
Prob >F	0.07	0.05	0.31	0.07	0.10

[+] At each depth, means within a column followed by the same letter are not significantly different ($\alpha = 0.05$)

[‡] Amp+ represents amplitude above the mean.

[§] Amp- represents amplitude below the mean.

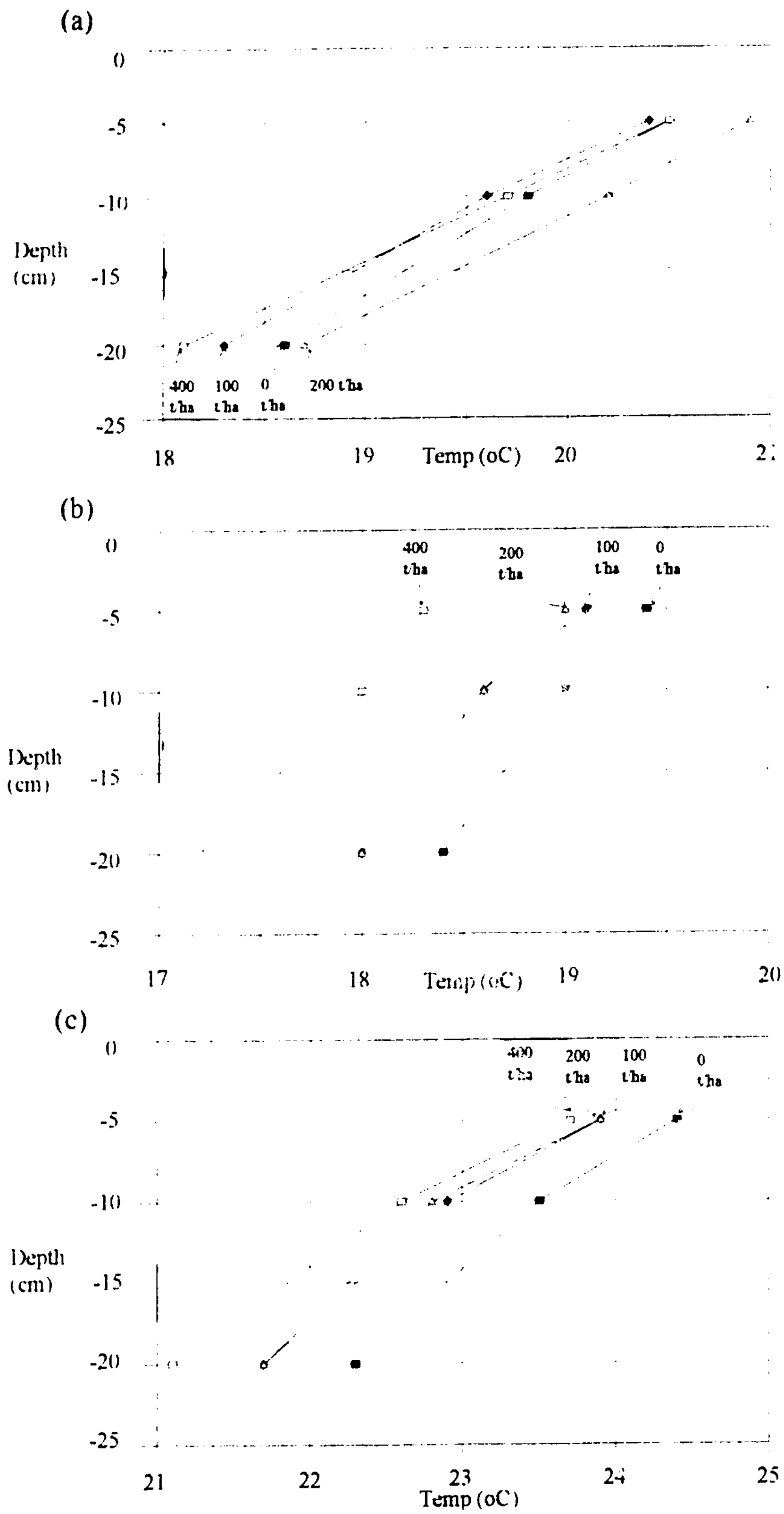

Figure 4-1. Mean daily temperature profiles of fly ash amended soils on: (a) June 17 and 18, 1993; (b) July 15, 1993; (c) July 28 and 29, 1994.

5. SYNTHESIS

Decades ago, industry and government were prompted by concerns over mass fly ash production to find a solution for an impending waste management problem. Since then, the hard work of researchers has yielded three potential sources of relief for this problem: utilization of ash for engineering purposes, extraction of metals, and the application of ash as a soil amendment. Utilization of the ash would provide the dual benefits of reducing waste management costs and providing a benefit to society. Fly ash application as a soil amendment might result in both physical and chemical benefits such as improving water infiltration and retention, reducing soil crusting, providing micronutrients for plants, and raising soil pH. As research continued, the chemical variability of fly ash among power stations and with time from the same power station became increasingly apparent. Fly ash contains several trace elements which could reach concentrations toxic to plants and animal. Although the general properties of fly ash are well known, insufficient field scale research has been conducted to determine the benefits, environmental consequences, and optimum rates of fly ash amendment on local problem soils.

The objectives of this research were to determine the nature and extent of influence of field application of fly ash on soil chemical properties; crop growth; development; and chemical composition, nutritional value of livestock feed; and soil temperature. From this study acceptable rates of fly ash application would be determined.

A field study was conducted on reclaimed land at the Highvale coal mine located 80 km west of Edmonton. The treatments included six rates of unweathered fly ash (0, 25, 50, 100, 200, and 400 t/ha) and four vegetation treatments (barley, brome, alfalfa, and unseeded control). Soil and plant samples were collected over two growing seasons for chemical analyses and determination of crop yield. Soil temperature data were collected from the 0, 100, 200, and 400 t/ha treatments.

5.1 SUMMARY

The following sections provide an overview of conclusions and general comments from for each of the objectives outlined above. Conclusions from this study may be restricted to the soils, crops, and fly ash which we used.

5.1.1 Overall Soil Properties

1. Water soluble B in the soil increased with fly ash rate to levels generally considered toxic for crops. However, B in the 0 to 15 cm depth decreased with time from application. The high B content of soils amended with fresh fly ash and subsequent B decrease with time has been well documented in literature (Carlson and Adriano, 1993). With leaching and plant uptake, soil B concentrations are expected to eventually decline to acceptable levels.
2. Soil pH increased with fly ash rate. Suitability of fly ash as a liming agent is limited by the likelihood of B toxicity at high application rates (Pluth et al., 1981).
3. Fly ash decreased the soluble Na:Ca ratio of the soil. Based on our results, fly ash could be used to reclaim problem soils with a high exchangeable sodium content. However, this benefit is not consistent among fly ashes from power stations across the province (Pluth et al., 1981).
4. Fly ash had no significant long term effect on soil salinity. Carlson and Adriano (1993) indicated that soil salinization would be greatly increased with the application of 100-400 t/ha of unweathered fly ash. However, in a lab experiment, Page et al. (1981) found that salt content was reduced by 30 % after a 30 day equilibration period. The results of Page et al. (1981) support our laboratory findings where salinity levels in fly ash mixed soils decreased quickly.
5. Bulk density of soils in this research increased with fly ash rate. These findings contradict the generalizations made by Carlson and Adriano (1993). With the assumption that the average bulk density of agricultural soils was 1.3 Mg/m^3, they indicated that bulk density would be lowered with fly ash application. In a literature

review, Sharma et al. (1989) showed that fly ash related change in Db was dependent on soil texture and bulk density prior to amendment.

6. Although not quantified, we observed an increase in soil erodibility and, when wet, a decrease in soil trafficability on the 200 and 400 t/ha treatments. With these observations we support the findings of other researchers (Carlson and Adriano, 1993).

5.1.2 Crop Growth, Development, And Chemical Composition

1. Based on soluble soil B, the high B in plant tissue, literature findings, and nature of symptoms, we have determined that high fly ash application rates resulted in B toxicity in barley and brome. Leaf necrosis due to B toxicity was the primary cause of yield reduction in barley. We expect the severity of B toxicity to decline with time due to reductions in soil B as described above.
2. Mo content of plant tissue increased with fly ash rate. After two years there was no indication of a reduction in Mo uptake by plants.
3. Due to leaf necrosis, B toxicity on the 200 and 400 t/ha fly ash treatments may influence the determination of barley kernel number per head at early growth stages, tiller survival at intermediate growth stages, and total kernel weight per head during kernel filling stages.
4. Intermediate fly ash treatments increased barley yield at soft dough stage. Yield results at other growth stages were confounded by non-treatment related factors such as flooding, disease, and geese.
5. Fly ash increased barley resistance to barley scald. The source of resistance could not be determined in this study but may be related to an increase in plant Ca content with fly ash rate.

5.1.3 Nutritional Value of Livestock Feed

1. Se concentration in livestock feed was increased from deficient to adequate by increasing plant available Se with fly ash application. Similar trends have been measured

by other researchers (Carlson and Adriano, 1993). This effect was observed only in the first year of our study and is only beneficial on Se deficient soils.

2. Fly ash related increase in plant available Mo increased the risk of molybdenosis disease in cattle due to an upset in dietary Cu:Mo balance. These observations were also made by previous researchers (Sharma et al., 1989). A copper supplement is necessary in livestock diets restricted to crops grown on fly ash amended soils.
3. B concentration in plant tissue from soils amended with high fly ash rates may reach concentrations considered toxic in livestock diets. This problem is expected to diminish with successive crops.

5.1.4 Soil Temperature

1. Mean daily soil temperature to a 20-cm depth was lowered with fly ash application rates $\geq$ 100 t/ha. These findings do not support generalizations made by Carlson and Adriano (1993). The extent of soil temperature decrease in our study was of negligible biological significance.

5.1.5 Fly Ash Application Rates

1. The greatest benefits of fly ash application were achieved at intermediate fly ash rates (50-200 t/ha). Despite measuring significant yield increase for some crops, the 200 t/ha rate should be considered the maximum acceptable rate of fly ash application due to problems associated with soil chemical (e.g. B toxicity and potential leaching) and physical properties (e.g. erosion, trafficability) and plant growth and development (e.g. yield reduction, delayed growth).
2. Aside from soil pH, the 25 t/ha treatment had little influence on soil chemical properties or chemical content and yield of crops.
3. The 400 t/ha fly ash treatment had the largest overall effect on soil properties and plant growth, development, and chemical content. Most of these effects were detrimental to overall ecosystem function. Acceptable fly ash application rates will be < 400 t/ha.

5.2 MARKETABILITY OF FLY ASH

Aside from farmer acceptance, the marketability of fly ash depends on three factors (Figure 5-1):

1. Is there a net economic benefit achieved from fly ash application?
2. What are the environmental consequences of economic benefit?
3. Can benefit be achieved more economically with another product?

These factors are in turn dependent upon a clear understanding of the properties of fly ash and its influence on soils and plants. From this research we have determined the influence of fly ash on soil chemical and physical properties, plant growth, development and chemical content, and livestock nutrition, identify target soils for fly ash application, and determine acceptable application rates. Further research is required to determine soil specific optimum application rates, sustainability of yield increase, and environmental impacts in an agricultural system.

5.3 FUTURE RESEARCH

To address the concern of fly ash as a waste management problem at the Sundance power station, further research is required.

1. Successful utilization of fly ash as an amendment will require a clear understanding of the extent of variability in fly ash chemistry with time. Variability of fly ash chemistry should be monitored initially on a weekly and then monthly basis for at least one year. Fly ash samples with extreme elemental concentrations (i.e. both high and low), especially B and possibly Se, As, Mo, Mn, should be collected, stock piled, and protected from weathering. Stockpiles should be large enough to supply a large field plot study.
2. A field study should be conducted which targets the worst, large scale, problem soils in the Highvale mine region, presumably Solonetzic soils. Both low and high B fly ashes should be applied at rates of 0, 50, 75, 100, 125, 150, and 200 t/ha. The fly ash should be incorporated by banding to a 10-15 cm depth to promote mixing and reduce potential loss due to erosion. Soil physical and chemical properties should be

monitored. If subsoil texture is loam, silt loam. or coarser, leaching studies may be required. Lateral flow of leachates over dense clayey B horizons should be monitored if the plots are located on sloping lands. Lateral flow is a significant process and may result in a concentration of trace elements in depressional areas or groundwater.

3. Vegetation treatments should include barley (B sensitive, shallow rooting, salt tolerant) and alfalfa (B tolerant, deep rooting, sensitive to salinity at establishment). Oats or any other local grown crop may be considered in rotation with barley. Barley yield at silage and maturity, and alfalfa yield at 10% bloom should be measured and chemical analysis should be conducted. Toxicity symptoms in barley should be monitored to assess the nature of nutrient imbalance. Total leaf area and necrosis may be measured at or during stem elongation stage and at early milk stage if desired but is not necessary.
4. This study should last at least 5 years to assess adequately whether enhanced yields are sustainable and if environmental risks are detected.

5.4 REFERENCES

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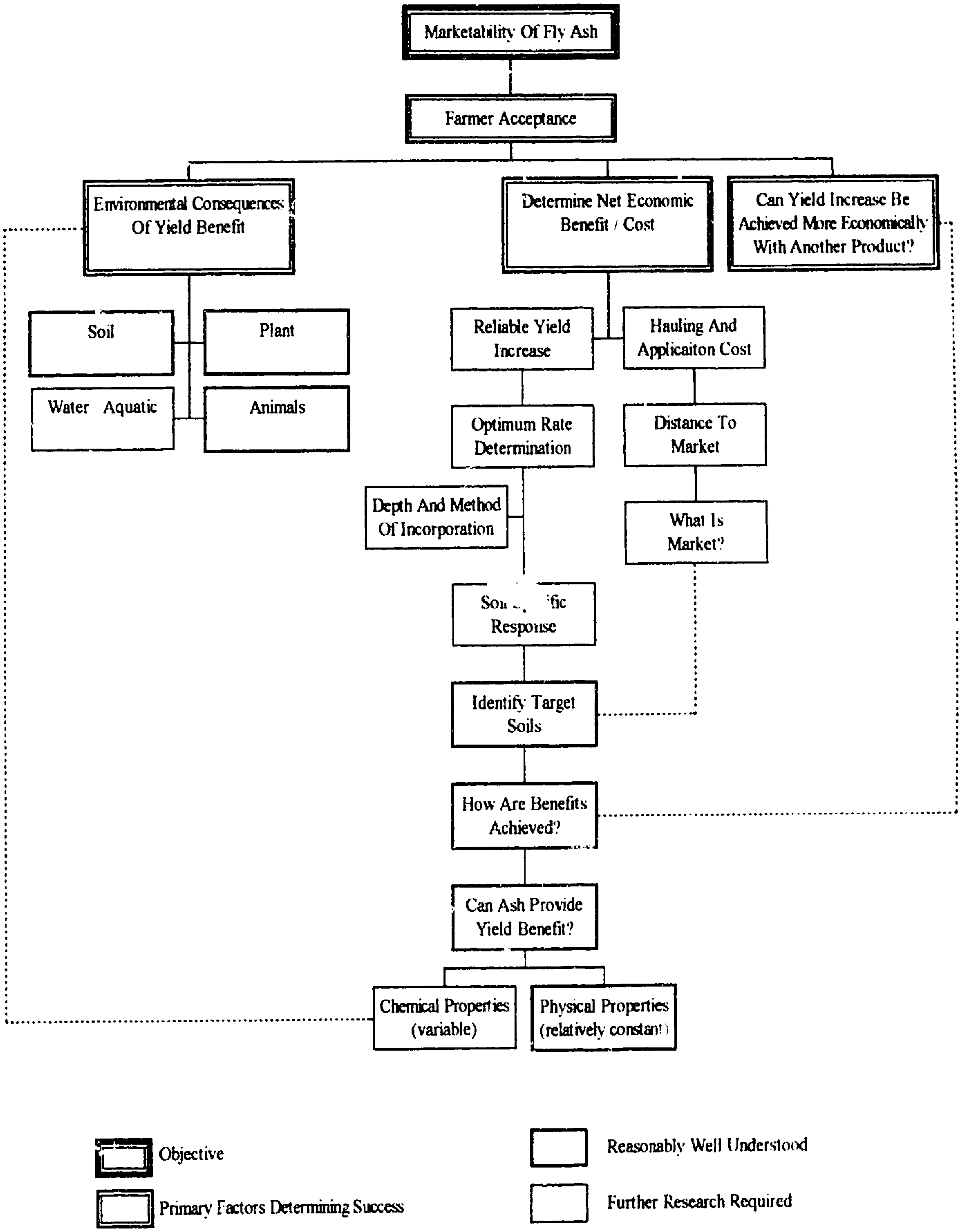

Figure 5-1. Factors influencing the suitability of fly ash as a soil amendment.

6. APPENDICES

6.1 CHEMICAL ANALYSIS OF FLY ASH AMENDED SOILS

Table 6-1. Mean saturation percentages and water soluble elemental concentration of fly ash amended soils. Means within a column for a given sample increment which are followed by the same letter are not significantly different (α=0.05).

Fly Ash	Sat	Ca	Mg	Na	K	Fe	Al	As	B
(t/ha)	(%)	(mg/L)						(ug/g)	
Spring 1993, 0-15 cm									
0	57	52 d	12 d	162 c	4.13 c	0.48 a	0.21 a	0.03 b	4.4 d
25	55	103 cd	24 bc	182 bc	6.03 b	0.36 a	0.10 b	0.04 b	5.2 cd
50	57	91 cd	19 cd	178 bc	5.71 bc	0.31 ab	0.11 b	0.02 b	5.1 cd
100	56	137 bc	27 bc	202 ab	7.08 ab	0.13 bc	0.05 b	0.03 b	6.3 c
200	55	163 b	29 ab	231 a	6.88 ab	0.10 c	0.03 b	0.04 b	8.4 b
400	55	257 a	36 a	226 a	8.46 a	0.09 c	0.03 b	0.08 a	13.3 a
Prob>F		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fall 1993, 0-15 cm									
0	59	50 e	10 e	129 c	3.66 d	0.54 a	0.20 a	0.00	2.2 d
25	56	84 ed	15 de	134 c	[illegible] cd	0.22 b	0.08 b	0.00	2.6 cd
50	58	12[illegible] cd	20 cd	160 bc	6.37 bc	0.22 b	0.07 bc	0.00	2.6 cd
100	58	164 bc	26 bc	176 b	6.97 abc	0.11 bc	0.04 bcd	0.00	4.3 bc
200	56	195 b	29 ab	222 a	7.76 ab	0.09 bc	0.01 cd	0.00	5.9 b
400	53	269 a	35 a	223 a	8.39 a	0.07 c	0.01 d	0.00	10.1 a
Prob>F		0.00	0.00	0.00	0.00	0.00	0.00	0.66	0.00
Spring 1993, 15-30 cm									
0	58	116	22	262	6.26	0.19	0.07	0.03	1.1
25	[illegible]	145	31	213	7.08	0.19	0.08	0.02	0.9
50	[illegible]	171	32	279	8.52	0.11	0.05	0.02	1.0
100	[illegible]	135	26	228	7.86	0.18	0.07	0.02	0.9
200	56	108	21	221	6.28	0.19	0.07	0.02	0.9
400	55	89	18	204	[illegible]	0.11	0.05	0.02	1.5
Prob>F		0.11	0.10	0.20	0.06	0.90	0.73	0.66	0.77
Fall 1993, 15-30 cm									
0	59	100	20	219	5.91	0.25	0.08	0.00	0.5
25	54	145	27	219	7.24	0.10	0.03	0.00	0.5
50	60	165	30	258	8.54	0.17	0.05	0.00	0.7
100	56	157	30	257	8.23	0.13	0.03	0.00	0.4
200	58	127	27	264	6.9	0.16	0.03	0.00	0.7
400	55	116	24	229	6.98	0.08	0.02	0.00	0.6
Prob>F		0.54	0.64	0.62	0.51	0.23	0.24	0.53	0.85

Table 6-1. (continued).

Fly Ash (t/ha)	Ba	Cr	Cu	Pb	Mo	P	Se	Sr	pH
	(ug/g)								
Spring 1993, 0-15 cm									
0	7.4	0.03 b	0.10	0.04	0.29 b	2.6	0.000	3.9	6.1 d
25	6.8	0.03 b	0.11	0.05	0.38 b	3.6	0.000	4.6	6.8 c
50	7.4	0.03 b	0.11	0.03	0.33 b	1.7	0.003	4.9	6.4 cd
100	7.5	0.04 b	0.10	0.05	0.41 b	1.8	0.000	5.0	6.7 c
200	6.0	0.08 b	0.12	0.01	0.44 b	2.0	0.002	5.2	7.3 b
400	4.8	0.29 a	0.07	0.01	0.71 a	2.7	0.006	5.9	7.8 a
Prob>F	0.09	0.00	0.54	0.35	0.00	0.19	0.41	0.14	0.00
Fall 1993, 0-15 cm									
0	5.5	0.08 b	0.05	0.00	0.01 d	0.8 cd	0.001 b	26.6	6.2 c
25	6.2	0.09 b	0.06	0.00	0.03 d	0.5 d	0.001 b	28.4	6.8 b
50	4.7	0.08 b	0.06	0.01	0.05 cd	1.1 bc	0.001 b	29.1	6.9 b
100	6.2	0.10 b	0.07	0.02	0.14 c	1.2 abc	0.001 b	36.4	7.1 b
200	5.5	0.09 b	0.07	0.05	0.26 b	1.3 ab	0.004 a	34.6	7.6 a
400	5.6	0.16 a	0.07	0.01	0.49 a	1.7 a	0.007 a	35.4	7.6 a
Prob>F	0.17	0.02	0.40	0.09	0.00	0.00	0.00	0.17	0.00
Spring 1993, 15-30 cm									
0	8.2	0.04	0.07	0.12	0.52	0.9	nd	10.4	7.0
25	8.8	0.06	0.0[illegible]	0.00	0.49	0.4		13.9	7.4
50	6.7	0.05	0.0[illegible]	0.00	0.48	0.4		14.6	7.1
100	7.6	0.05	0.04	0.00	0.46	0.1		13.0	7.1
200	6.9	0.04	0.0[illegible]	0.02	0.50	0.6		9.4	7.1
400	8.0	0.04	0.03	0.00	0.44	0.2		10.1	7.3
Prob>F	0.91	0.60	0.58	0.34	0.93	0.54		0.78	0.69
Fall 1993, 15-30 cm									
0	8.4	0.06	0.08	0.04	0.00	1.5	nd	12.4	6.5
25	9.7	0.06	0.11	0.01	0.00	1.1		10.2	7.1
50	9.5	0.06	0.14	0.09	0.00	2.3		14.2	6.9
100	8.7	0.05	0.09	0.03	0.01	1.3		7.3	6.8
200	12.4	0.05	0.15	0.17	0.02	2.8		17.1	6.9
400	7.3	0.05	0.09	0.02	0.00	1.1		11.8	6.9
Prob>F	0.23	0.86	0.26	0.33	0.52	0.36		0.35	0.33

Table 6-1. (continued)

Fly Ash (t/ha)	SAT (%)	Ca	Mg	Na	K	Fe	Al	B
		(mg/L)						(ug/g)
Spring 1994, 0-15 cm								
0	60	72 d	14 c	177 cd	6.1	0.19 a	0.10 a	3.9
25	60	117 cd	20 bc	159 d	6.8	0.07 b	0.04 b	4.6
50	61	147 bc	26 ab	180 cd	7.5	0.06 b	0.03 b	4.4
100	59	193 b	33 a	195 bc	7.5	0.05 b	0.04 b	3.9
200	57	219 ab	37 a	232 a	7.4	0.06 b	0.03 b	4.9
400	53	276 a	37 a	223 ab	8.4	0.05 b	0.02 b	5.8
Prob>F		0.00	0.00	0.00	0.26	0.00	0.00	0.08
Fall 1994, 0-15 cm								
0	61	40 c	10 c	129 c	3.7 bc	0.71 a	0.18 a	1.2 c
25	60	79 bc	14 bc	125 c	3.4 c	0.33 bc	0.08 bc	1.2 c
50	60	62 bc	13 bc	139 bc	4.3 abc	0.57 ab	0.12 b	1.6 bc
100	60	101 b	19 ab	159 abc	4.8 abc	0.10 c	0.05 c	1.6 bc
200	59	103 ab	20 ab	178 ab	5.0 ab	0.11 c	0.05 c	2.1 ab
400	56	149 a	24 a	199 a	5.7 a	0.10 c	0.05 c	2.9 a
Prob>F		0.00	0.02	0.00	0.02	0.00	0.00	0.00
Spring 1994, 15-30 cm								
0	61	83	17	236	6.0	0.33	0.07	4.1
25	60	123	22	210	7.0	0.18	0.07	4.1
50	59	121	26	231	7.0	0.09	0.04	4.2
100	59	135	26	246	7.7	0.14	0.05	3.8
200	66	146	29	276	7.4	0.08	0.04	4.2
400	60	142	28	251	6.9	0.05	0.03	4.0
Prob>F		0.78	0.65	0.51	0.24	0.06	0.18	0.99
Fall 1994, 15-30 cm								
0	61	50 b	11 c	184 c	4.2 b	0.67	0.18 a	1.1 c
25	63	96 ab	22 ab	204 abc	4.5 b	0.30	0.07 b	1.1 c
50	64	69 b	16 bc	189 bc	4.4 b	0.44	0.11 b	1.3 bc
100	61	60 b	18 abc	176 c	4.6 b	0.41	0.09 b	1.5 abc
200	66	94 ab	21 ab	245 a	5.3 ab	0.10	0.06 b	1.6 ab
400	57	135 a	25 a	239 ab	6.0 a	0.12	0.05 b	1.9 a
Prob>F		0.01	0.05	0.05	0.06	0.11	0.00	0.01

Table 6-1. (continued).

Fly Ash (t/ha)	Ba	Mn	P	S	Se	Sr	Zn	pH
				(ug/g)				
Spring 1994, 0-15 cm								
0	14	4.42 a	0.33 bc	67	66 b	7.1 b	0.53	6.0 c
25	22	0.77 b	0.13 c	106	76 b	9.4 b	0.47	6.8 b
50	19	0.62 b	0.36 bc	84	67 b	8.2 b	0.62	6.7 b
100	42	0.50 b	0.72 bc	95	93 b	8.8 b	0.45	7.1 b
200	20	0.28 b	1.31 b	118	101 b	9.5 b	0.33	7.7 a
400	27	0.27 b	2.65 a	136	177 a	12.2 a	0.36	8.0 a
Prob>F	0.18	0.02	0.00	0.18	0.00	0.01	0.20	0.00
Fall 1994, 0-15 cm								
0	41	2.17	0.44 b	70	72 b	7.4 d	0.73	6.4 c
25	32	1.52	1.25 ab	90	121 b	8.8 bc	1.64	7.0 b
50	39	1.94	1.16 ab	82	88 b	8.3 cd	0.72	6.8 bc
100	26	2.00	1.15 ab	94	108 b	10.1 ab	0.71	7.2 b
200	29	0.38	2.04 a	89	112 b	11.4 a	0.52	7.9 a
400	13	1.45	1.68 a	121	183 a	11.3 a	0.46	7.9 a
Prob>F	0.25	0.26	0.04	0.20	0.01	0.00	0.36	0.00
Spring 1994, 15-30 cm								
0	23	2.68	0.34	114 a	51	7.03	0.59	6.3
25	24	1.32	0.61	139 a	56	8.34	0.61	6.9
50	15	1.98	0.17	231 a	40	7.6	0.47	6.6
100	24	1.18	0.35	183 a	72	8.67	0.44	6.9
200	18	0.69	0.49	172 a	61	7.02	0.41	6.9
400	24	1.98	0.38	151	52	7.47	0.54	6.7
Prob>F	0.7	0.36	0.86	0.85	0.74	0.52	0.22	0.24
Fall 1994, 15-30 cm								
0	39	3.68	0.59	90	79	8.39	0.62	6.5
25	28	1.58	1.25	117	93	9.13	1.41	7.4
50	47	2.97	0.98	101	87	7.89	0.75	6.9
100	37	1.73	0.96	102	84	8.71	0.58	6.9
200	48	1.80	1.00	137	88	8.35	0.65	7.1
400	24	1.70	0.62	148	107	7.93	0.55	6.8
Prob>F	0.80	0.54	0.67	0.10	0.96	0.66	0.14	0.07

nd not determined

6.2 CHEMICAL ANALYSIS OF PLANT MATERIALS GROWN ON FLY ASH AMENDED SOILS

Table 6-2. Mean elemental concentration of vegetation grown on fly ash amended soil. Means in a column of a vegetation treatment followed by the same letter are not significantly different (α=0.05).

Fly Ash	N	P	K	S	Ca	Mg	Na	Al	As	B
(t/ha)				(%)					(µg/g)	
Alfalfa, 1993										
0	4.07	0.28	1.95	0.43	1.93	0.23	0.10	175	0.013	49 b
25	3.78	0.26	1.62	0.37	1.85	0.23	0.08	137	0.007	59 b
50	3.95	0.29	1.68	0.39	1.76	0.22	0.07	185	0.013	56 b
100	4.10	0.30	1.84	0.40	1.74	0.22	0.06	152	0.008	60 b
200	4.08	0.30	1.69	0.43	1.88	0.23	0.09	142	0.015	90 ab
400	4.05	0.26	1.96	0.44	1.89	0.22	0.11	230	0.022	139 a
Prob>F	0.80	0.10	0.55	0.12	0.30	0.80	0.56	0.18	0.74	0.03
Barley Silage, 1993										
0	1.67	0.12	1.14	0.29	0.31 d	0.11 b	0.55	59	0.026 c	1 c
25	1.58	0.13	1.12	0.33	0.33 cd	0.11 b	0.58	82	0.029 bc	12 c
50	1.83	0.17	1.10	0.28	0.34 bcd	0.12 b	0.44	70	0.018 c	10 c
100	2.08	0.19	1.21	0.31	0.45 abc	0.14 a	0.39	73	0.043 ab	42 bc
200	2.09	0.16	1.15	0.35	0.46 ab	0.12 ab	0.59	78	0.052 a	84 b
400	2.57	0.23	1.18	0.34	0.51 a	0.14 a	0.47	70	0.046 a	150 a
Prob>F	0.10	0.00	0.96	0.70	0.02	0.05	0.67	0.85	0.01	0.00
Barley Straw, 1993										
0	0.80 b	0.07 b	1.08 bc	0.29 bcd	0.35 b	0.08 bc	0.72	74	0.013	5 c
25	0.63 b	0.08 b	0.96 c	0.22 d	0.34 b	0.07 c	0.56	119	0.017	11 c
50	1.09 b	0.09 b	1.08 bc	0.25 cd	0.41 b	0.07 c	0.54	120	0.028	15 c
100	1.01 b	0.10 b	1.31 ab	0.33 abc	0.46 b	0.08 bc	0.63	85	0.008	26 c
200	1.15 b	0.12 b	1.15 abc	0.39 a	0.61 a	0.11 ab	0.69	161	0.023	68 b
400	1.82 a	0.18 a	1.38 a	0.38 ab	0.67 a	0.12 a	0.68	131	0.033	119 a
Prob>F	0.03	0.01	0.05	0.01	0.00	0.02	0.40	0.87	0.13	0.00
Brome, 1993										
0	4.59	0.30 c	2.50	0.41	0.44	0.17 c	0.02	172	0.007	9 d
25	4.55	0.30 c	2.49	0.45	0.45	0.17 bc	0.02	202	0.010	13 cd
50	4.63	0.31 c	2.53	0.42	0.47	0.16 c	0.02	315	0.015	30 bc
100	4.52	0.32 bc	2.47	0.46	0.48	0.18 bc	0.01	170	0.013	33 b
200	5.18	0.36 a	2.61	0.45	0.50	0.19 ab	0.02	185	0.013	45 b
400	5.41	0.35 ab	2.67	0.46	0.55	0.20 a	0.02	222	0.012	78 a
Prob>F	0.07	0.01	0.53	0.49	0.10	0.01	0.53	0.28	0.93	0.00
Barley Grain, 1993										
0	1.90	0.29	0.42	0.15 c	0.04	0.13	0.05	172	0.000	0 b
25	1.85	0.31	0.46	0.15 c	0.04	0.12	0.05	175	0.003	0 b
50	1.84	0.32	0.44	0.14 c	0.05	0.13	0.04	846	0.022	1 b
100	1.94	0.33	0.46	0.15 c	0.04	0.13	0.05	86	0.005	1 b
200	2.14	0.34	0.47	0.17 b	0.05	0.12	0.10	115	0.008	8 ab
400	2.24	0.39	0.59	0.18 a	0.06	0.13	0.09	246	0.009	12 a
Prob>F	0.06	0.28	0.11	0.00	0.07	0.88	0.23	0.37	0.47	0.05

Table 6-2. (continued).

Flv Ash	Ba	Cr	Cu	Fe	Mn	Mo	Se	Sr	Zn	ADF
(t/ha)					(ug/g)					(%)
Alfalfa, 1993										
0	46	3.57	9.60 b	167	69	1.7 d	0.03 d	105	35.3	21 b
25	29	2.70	12.63 a	146	83	5.7 c	0.09 cd	105	36.4	23 a
50	30	3.50	9.67 b	158	45	7.7 bc	0.12 bcd	97	33.6	22 ab
100	29	3.03	9.40 b	149	48	10.2 b	0.33 ab	97	36.2	22 ab
200	22	5.33	9.63 b	143	50	14.5 a	0.30 abc	71	34.7	21 b
400	25	3.70	8.97 b	169	45	8.5 bc	0.36 a	112	31.6	21 b
Prob>F	0.11	0.54	0.04	0.85	0.27	0.00	0.03	0.43	0.53	0.04
Barley Silage, 1993										
0	13	3.50	5.47	92	72	0	0.19	21	29.2	32
25	18	4.83	5.30	109	58	0	0.15	24	29.9	33
50	17	3.43	6.17	102	52	1.5	0.26	21	36.5	31
100	19	4.20	6.13	115	76	2.73	0.29	28	33.8	30
200	13	3.67	6.17	101	51	4.5	0.32	30	24.6	31
400	14	2.33	6.47	108	89	2.73	0.43	32	33.7	29
Prob>F	0.54	0.60	0.45	0.78	0.36	0.09	0.19	0.12	0.30	0.09
Barley Straw, 1993										
0	31	0.00	4.67 b	130	138	0 b	0.02 b	33 b	28.2	47 b
25	30	0.00	3.67 c	174	64	1.33 b	0.07 b	31 b	22.9	50 a
50	31	0.00	4.00 bc	163	61	0 b	0.14 b	37 b	21.6	49 ab
100	34	0.00	4.50 bc	127	91	1.67 b	0.14 b	37 b	26.2	48 b
200	32	1.33	4.83 b	181	101	7.07 a	0.28 b	50 a	20.6	45 c
400	32	1.13	6.00 a	185	132	5.57 a	0.58 a	53 a	29.7	42 d
Prob>F	0.98	0.47	0.01	0.75	0.06	0.00	0.00	0.00	0.43	0.00
Brome, 1993										
0	12	2.60	13.27	148	139 a	0 c	0.12 d	26 c	42.8	24
25	18	3.00	14.43	159	94 b	0.73 c	0.10 d	27 c	42	24
50	23	4.20	10.93	174	126 a	2.5 bc	0.20 cd	34 ab	48.7	23
100	15	4.90	12.97	163	94 b	3.73 abc	0.34 bc	29 bc	41.1	23
200	17	6.17	13.80	165	82 b	5.47 ab	0.47 ab	31 bc	42.5	22
400	18	5.53	13.10	166	92 b	6.73 a	0.56 a	36 a	45.2	21
Prob>F	0.35	0.73	0.17	0.98	0.00	0.02	0.00	0.01	0.42	0.12
Barley Grain, 1993										
0	5	5.37	10.43	168	27	0.0	0.24	3	49.1	8
25	6	3.71	9.20	149	22	0.3	0.30	3	43.2	8
50	11	4.21	12.20	449	27	0.3	0.38	4	45.8	9
100	5	5.30	10.60	113	23	0.5	0.25	4	49.3	8
200	4	3.56	8.10	130	23	1.4	0.33	4	42	7
400	6	1.91	10.60	255	31	0.3	0.44	5	52	8
Prob>F	0.13	0.70	0.76	0.48	0.36	0.47	0.22	0.19	0.71	0.46

Table 6-2. (continued).

Fly Ash (t/ha)	N	P	K	S	Ca	Mg	Na	Al	As	B
				(%)				(ug/g)		
Alfalfa Cut 1, 1994										
0	2.52 c	0.02	nd	0.03	0.11	0.01	0.01	112	nd	64 d
25	2.68 bc	0.02		0.03	0.12	0.01	0.01	135		69 cd
50	2.92 ab	0.02		0.03	0.12	0.01	0.01	97		71 cd
100	2.90 ab	0.02		0.03	0.11	0.01	0.00	107		74 c
200	2.94 ab	0.02		0.03	0.11	0.01	0.01	112		94 b
400	2.99 a	0.02		0.03	0.12	0.01	0.01	151		115 a
Prob>F	0.02	0.16		0.53	0.40	0.56	0.10	0.36		0.00
Alfalfa Cut 2, 1994										
0	3.31 a	0.02 b		0.03 bc	0.10	0.01	0.00	87		64 c
25	3.25 ab	0.02 ab		0.04 a	0.11	0.01	0.00	87		70 bc
50	3.17 ab	0.02 a		0.03 ab	0.10	0.01	0.00	90		70 bc
100	2.94 bc	0.02 b		0.03 c	0.10	0.01	0.00	96		76 b
200	3.03 abc	0.02 a		0.03 bc	0.10	0.01	0.00	116		80 b
400	2.81 c	0.02 ab		0.03 c	0.10	0.01	0.00	72		97 a
Prob>F	0.05	0.04		0.01	0.53	0.83	0.72	0.21		0.00
Barley Boot, 1994										
0	2.78	0.02 c		0.03 a	0.02 d	0.01	0.04 b	56		18 b
25	2.80	0.03 bc		0.03 b	0.03 cd	0.01	0.04 b	47		22 b
50	2.61	0.03 bc		0.03 a	0.03 bcd	0.01	0.04 b	52		22 b
100	3.07	0.03 ab		0.03 a	0.03 bc	0.01	0.03 b	42		31 b
200	3.14	0.03 ab		0.03 a	0.03 b	0.01	0.05 a	42		35 b
400	3.63	0.03 a		0.03 a	0.04 a	0.01	0.05 a	57		71 a
Prob>F	0.13	0.02		0.05	0.00	0.12	0.01	0.27		0.00
Barley Soft Dough, 1994										
0	2.21	0.02		0.02	0.02	0.01 a	0.04 ab	86		37 c
25	2.19	0.02		0.02	0.02	0.01 b	0.03 bc	91		43 bc
50	2.13	0.02		0.02	0.02	0.01 b	0.03 bc	119		47 bc
100	2.37	0.02		0.02	0.03	0.01 a	0.03 c	90		58 b
200	2.29	0.02		0.02	0.02	0.01 b	0.04 ab	84		62 b
400	2.58	0.02		0.02	0.03	0.01 a	0.05 a	90		106 a
Prob>F	0.44	0.32		0.25	0.06	0.03	0.03	0.36		0.00
Barley Grain, 1994										
0	1.65	0.03		0.01 c	0.00	0.01	0.01	126		38
25	1.57	0.03		0.02 bc	0.00	0.01	0.01	287		39
50	1.52	0.04		0.02 bc	0.00	0.01	0.01	97		37
100	1.73	0.04		0.01 bc	0.00	0.01	0.01	166		40
200	1.77	0.04		0.02 b	0.00	0.01	0.01	133		42
400	2.09	0.04		0.02 a	0.00	0.01	0.01	98		45
Prob>F	0.10	0.31		0.01	0.11	0.93	0.14	0.22		0.08

Table 6-2 (continued)

Fly Ash (t/ha)	Ba	Cr	Cu	Fe	Mn	Mo	Se	Sr	Zn	ADF (%)
	(ug/g)									
Alfalfa Cut 1, 1994										
0	44	1.78 b	7.02 a	85	26	1.9 c	0.46	102	18	33
25	37	1.67 b	6.07 abc	127	27	2.5 bc	0.22	99	19	33
50	36	1.53 b	6.73 ab	92	19	3.3 bc	0.52	111	18	33
100	32	1.50 b	5.84 bc	125	16	3.9 b	0.29	98	20	34
200	24	7.39 a	6.00 bc	105	18	8.1 a	0.48	101	18	30
400	22	2.26 b	5.48 c	136	19	6.8 a	0.31	94	20	33
Prob>F	0.11	0.00	0.05	0.08	0.29	0.00	0.19	0.55	0.93	0.12
Alfalfa Cut 2, 1994										
0	43	2.19	7.60	74	27	2.7 c	0.14 bc	94	20	32
25	44	1.76	7.37	85	26	3.1 bc	0.36 a	94	20	31
50	36	2.65	7.46	79	22	3.6 bc	0.05 c	92	19	33
100	32	1.69	6.70	96	16	4.3 b	0.19 abc	89	16	31
200	33	2.86	7.09	114	21	5.9 a	0.04 c	99	18	32
400	26	4.23	6.99	84	22	6.5 a	0.31 ab	87	17	30
Prob>F	0.17	0.40	0.45	0.25	0.37	0.00	0.02	0.58	0.36	0.72
Barley Boot, 1994										
0	13	1.08	7.84	92	53	1.2 c	0.00	21 c	30	32 bc
25	16	1.16	7.10	82	27	1.5 c	0.03	22 bc	55	33 ab
50	16	1.34	8.04	76	25	2.4 bc	0.00	26 bc	29	35 a
100	17	1.19	7.71	74	34	3.7 b	0.02	26 bc	30	33 ab
200	13	1.23	7.47	75	29	5.3 a	0.03	29 b	25	33 ab
400	15	1.02	6.66	99	39	6.2 a	0.00	38 a	24	30 c
Prob>F	0.58	0.75	0.69	0.58	0.34	0.00	0.81	0.00	0.46	0.03
Barley Soft Dough, 1994										
0	17	1.17	6.65	74	44	1.3 d	0.00	19	99	31
25	22	1.30	5.68	76	24	1.6 d	0.00	21	32	31
50	21	1.10	5.78	89	24	1.8 cd	0.00	21	24	35
100	22	1.28	6.39	80	29	3.0 c	0.05	22	41	34
200	21	1.03	5.47	81	27	4.7 b	0.00	23	24	37
400	18	1.34	5.17	80	37	6.9 a	0.01	25	36	30
Prob>F	0.13	0.35	0.21	0.97	0.12	0.00	0.54	0.17	0.46	0.29
Barley Grain, 1994										
0	12 b	1.45 b	10.81	166	26	1.1 d	0.40	6	42	9
25	18 a	1.90 a	10.58	184	19	1.3 d	0.24	6	42	9
50	12 b	1.53 b	10.23	113	19	1.4 cd	0.34	5	39	9
100	14 b	1.50 b	10.82	160	20	2.0 bc	0.41	6	38	10
200	13 b	1.50 b	12.01	140	21	2.5 b	0.29	6	40	10
400	13 b	1.37 b	8.75	92	23	3.6 a	0.31	6	39	10
Prob>F	0.02	0.03	0.35	0.48	0.16	0.00	0.94	0.67	0.96	0.52

Table 6-2. (continued).

Fly Ash (t/ha)	N	P	K	S	Ca	Mg	Na	Al	As	B
	(%)							(ug/g)		
Barley Straw, 1994			nd						nd	
0	1.34	0.01		0.02	0.02	0.01	0.05	163		51
25	1.17	0.01		0.02	0.02	0.01	0.04	206		42
50	1.04	0.01		0.02	0.02	0.00	0.04	151		45
100	1.18	0.01		0.02	0.02	0.00	0.04	189		49
200	1.08	0.01		0.02	0.02	0.00	0.06	120		46
400	1.60	0.01		0.02	0.03	0.01	0.05	150		74
Prob>F	0.24	0.69		0.85	0.44	0.28	0.07	0.77		0.11
Brome, 1994										
0	1.49	0.01		0.01	0.01 b	0.01	0.00	59		48 d
25	1.48	0.01		0.01	0.01 b	0.01	0.00	52		51 d
50	1.76	0.01		0.01	0.02 b	0.01	0.00	56		57 cd
100	1.59	0.01		0.01	0.01 b	0.01	0.00	55		60 c
200	1.72	0.01		0.02	0.02 b	0.01	0.00	55		72 b
400	2.12	0.01		0.02	0.02 a	0.01	0.00	59		95 a
Prob>F	0.12	0.26		0.07	0.02	0.10	0.18	0.93		0.00

Table 6-2. (continued).

Fly Ash (t/ha)	Ba	Cr	Cu	Fe	Mn	Mo	Se	Sr	Zn	ADF
	(ug/g)									(%)
Barley Straw, 1994										
0	27	2.21 a	5.89 a	101	46	1.5 b	0.19	18	35	38 d
25	30	1.18 b	4.84 ab	142	32	1.4 b	0.13	21	22	45 c
50	30	1.67 a	4.59 b	86	28	1.7 b	0.23	21	21	49 a
100	27	1.34 b	4.62 b	118	27	2.6 b	0.18	18	20	46 c
200	28	1.17 b	4.20 b	101	26	4.4 a	0.32	20	86	49 a
400	23	1.57 b	3.69 b	121	37	5.4 a	0.24	26	20	42 b
Prob>F	0.56	0.05	0.04	0.65	0.25	0.00	0.55	0.52	0.60	0.00
Brome, 1994										
0	14	1.21	4.07	45	54	1.1 d	0.17	14 c	16	41
25	14	0.97	4.05	60	36	1.4 cd	0.17	14 c	14	39
50	11	1.12	4.53	407	59	1.5 bd	0.19	17 b	19	39
100	12	1.14	3.95	56	44	2.3 b	0.15	15 bcd	16	39
200	11	1.29	4.32	58	29	2.1 bc	0.10	14 cd	16	39
400	12	0.99	5.15	50	41	3.3 a	0.24	19 a	18	38
Prob>F	0.35	0.87	0.09	0.42	0.08	0.00	0.77	0.00	0.47	0.41

6.3 TEMPERATURE OF FLY ASH AMENDED SOIL

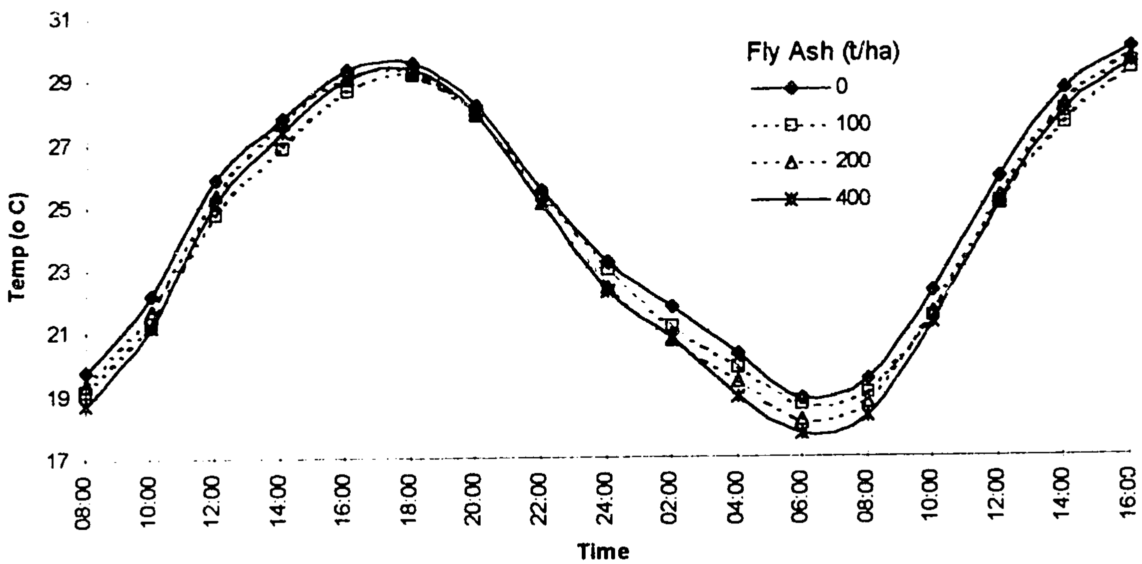

Figure 6-1. Diurnal mean soil temperature of fly ash treatments at 5-cm depth, July 28-29, 1994.

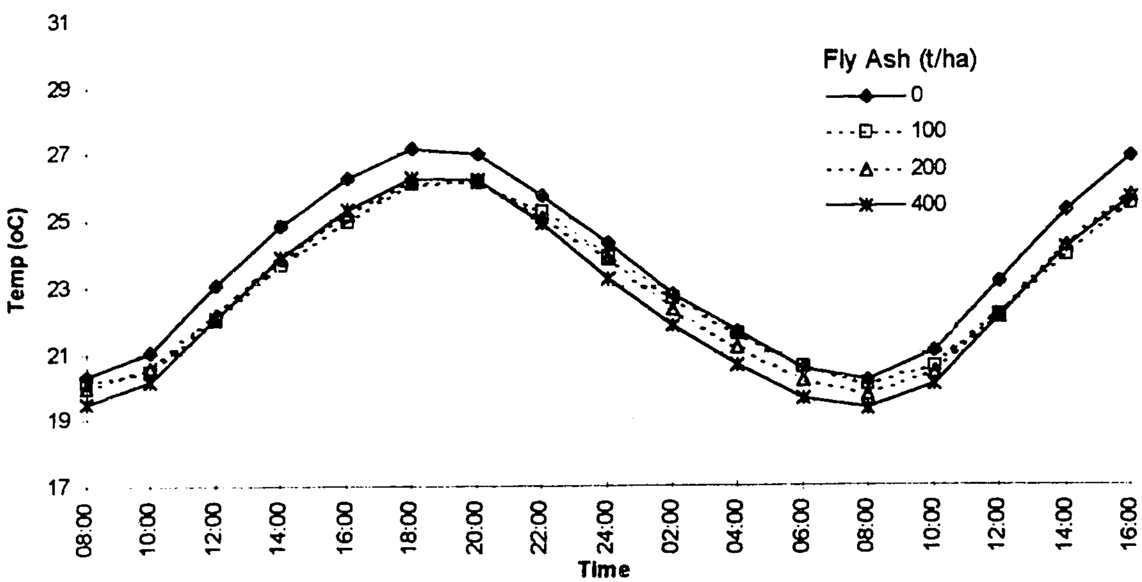

Figure 6-2. Diurnal mean soil temperature of fly ash treatments at 10-cm depth, July 28-29, 1994.

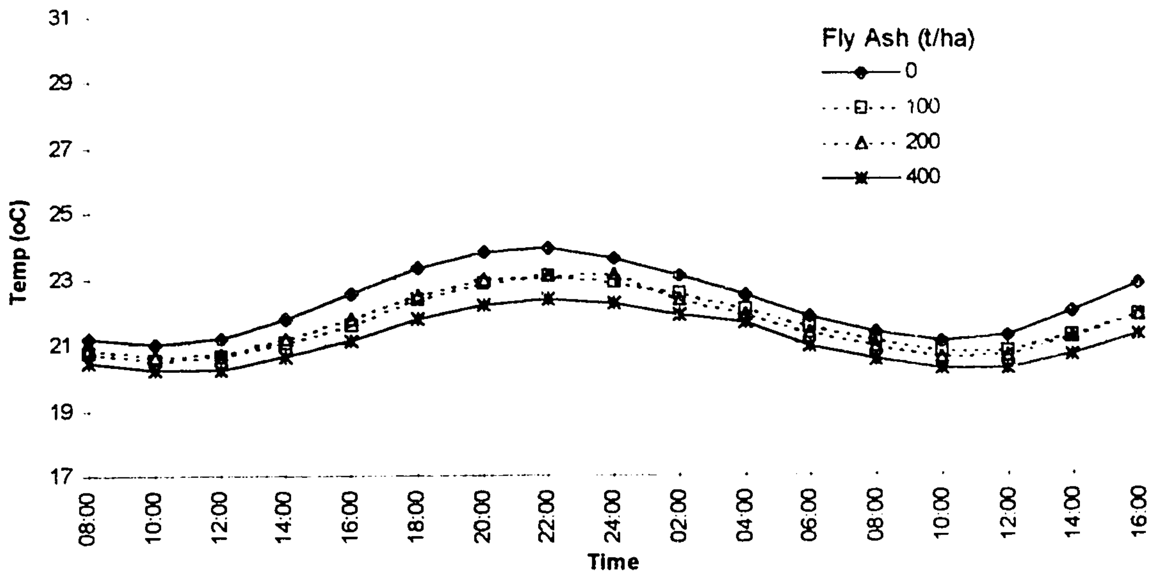

Figure 6-3. Diurnal mean soil temperature of fly ash treatments at a 20-cm depth, July 28-29, 1994.

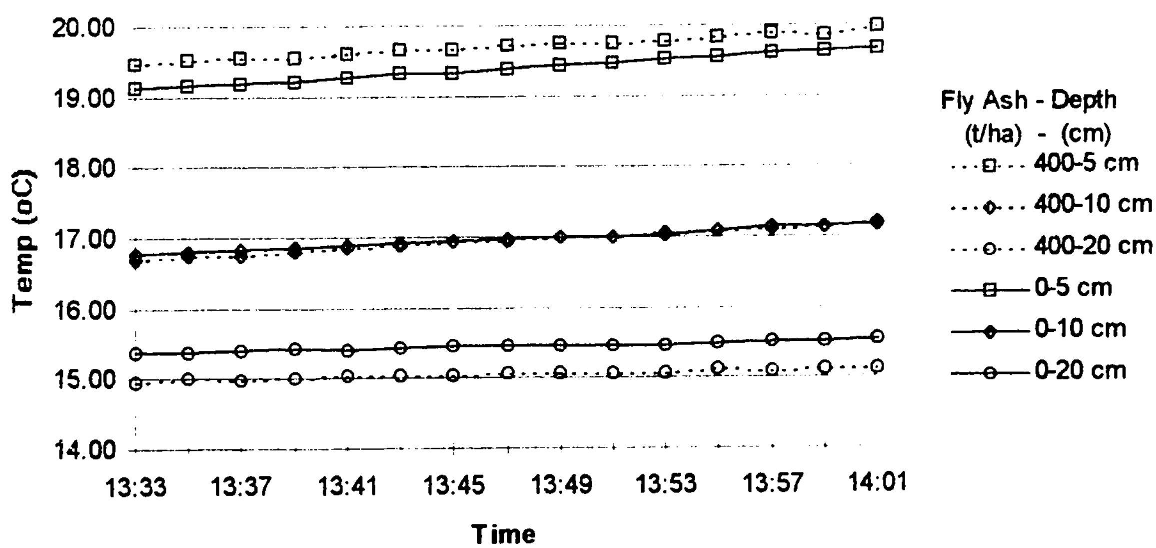

Figure 6-4. Soil temperature change over a twenty eight minute period for the 0 and 400 t/ha fly ash treatments, June 17, 1993.