# THE AGRONOMIC BENEFIT OF PULP MILL BOILER WOOD ASH

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Bachelor of Science
(Agricultural Biotechnology, University of Lethbridge, 1998)

A Thesis Submitted to the
School of Graduate Studies Council of the
University of Lethbridge
In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

UNIVERSITY OF LETHBRIDGE
LETHBRIDGE, ALBERTA, CANADA

May 2001

## ABSTRACT

Land application of wood ash is becoming more appealing, as a disposable alternative, to landfilling options. It is estimated that 110, 000 tonnes of wood ash is produced annually in Alberta by cogeneration systems, a large percentage produced in Central and Peace River Regions of Alberta. Alkaline (pH~13) properties and nutrient content of wood ash provides an alternative for the acidic and nutrient deficient soils within these regions. The objective of this field study was to determine the effect wood ash applications would have under field conditions on: the chemical and physical properties of soils; barley dry matter production; grain and seed yield of barley and canola; and the nutrient and metal uptake by crop tissue. Ash applications significantly increased dry matter and seed yield, improved crop nutrient quality, increased soil pH and improved soil nutrient availability, while not infringing on any environmental regulations.

## EXECUTIVE SUMMARY

Over the last few years there has been increasing focus on reducing the volume of material deposited into industrial and municipal landfills. With increasing focus placed on waste reduction through recycling, responsible waste management plans need to be developed with minimal environmental impacts. One area of research involves the land application of wood ash and its use as both a nutrient supplement as well as an alternative to agricultural lime.

It is estimated in Alberta, nearly 110, 000 tonnes (t) of wood ash is produced annually by companies operating cogeneration facilities. Cogeneration involves the simultaneous generation of heat, steam and electricity as a result of the burning wood waste or fossil fuels (Suncor Energy, 1999). Wood ash is the waste by – product produced from the incineration of wood wastes, like bark and knots used as fuel in these systems. Until recently landfilling has been the only available disposal option for wood ash. However, the nutrient content and alkaline pH of wood ash make it useful as a nutrient supplement and an agricultural lime alternative. Alberta currently does not have any guidelines pertaining to the land application of wood ash as a soil amendment. Land application of wood ash is currently regulated through guidelines established for other industrial and municipal wastes by Alberta Tier – 1 Guidelines for Contaminated Sites and Canadian Council of Ministers for the Environment (CCME). Alberta Environment, in association with various mills across Alberta, is in the process of addressing this issue.

This field study was established to evaluate the environmental and agronomic aspects surrounding the land application of wood ash. The project addressed issues of potential application rates, nutrient and metal loading within the soil profile, effects on crop productivity, and plant uptake of various nutrients and metals.

The field study consisted of three replications of the following four wood ash application rates: control (0), 6, 12.5, and 25 t $ha^{-1}$. Wood ash application rates used in this

study were considered to be equivalent to liming rates used for commercial agricultural production. The site chosen for the study is located in the Luvisolic Soil zone of Central Alberta, and consisted primarily of Orthic Gray Luvisols. Soil groups in this order often tend to be acidic with pH ranging from 5 to 6. A Side Discharge Manure Spreader was used to apply the wood ash that was then incorporated, by disc, to a depth of 0.20-m. Half of each plot was fertilized with nitrogen fertilizer (46-0-0) to provide 130 kg $ha^{-1}$ of nitrogen. The plots were seeded with two barley cultivars (*H. vulgare* L. cv 'AC Lacombe' and cv. 'Harrington') and a Polish canola cultivar (*B. rapa* L. cv. 'Maverick') chosen for the study based on their short maturation and common use in the study area.

Wood ash used in this study has an alkaline pH (pH = 13) with a calcium carbonate equivalence averaging 50%. In addition, the ash contains moderate levels of calcium (Ca), potassium (K), magnesium (Mg), phosphorus (P), and sulphur (S) and low levels of trace elements like boron (B) and zinc (Zn). However, cadmium (Cd) is also present in the ash, which at high application rates may pose an environmental problem. Cadmium, a heavy metal, if ingested can result in liver and kidney damage due to its bioaccumulation within animal and human tissues. Close attention was paid to specific environmental parameters such as soil pH, electrical conductivity (EC), and soil loading of hot water soluble B ($B_{HWS}$), Cd, and Zn with particular attention paid to the plant uptake of these elements.

Soil pH and EC was monitored throughout the study period from 1998 to 2000. Ash applications increased soil pH and EC but remained below upper limits set by Alberta Tier – 1 Guidelines for Contaminated Sites. Soil pH did not exceed 7.7, even with the highest application of wood ash (25 t $ha^{-1}$). Soil chemical analysis for $B_{HWS}$, total Cd, and total Zn showed no concerns after applications up to 25 t $ha^{-1}$ of wood ash. Levels were all below upper limits set under Alberta Tier – 1 of 2.0 mg $kg^{-1}$ for $B_{HWS}$, 1.0 mg $kg^{-1}$ for Cd, and 120 mg $kg^{-1}$ for Zn. Additional soil analysis from plots containing ash applications showed significant increases in available levels of B, K, S, and Zn while, significant decreases in available iron (Fe) were observed. The reduced availability of Fe in the soil may be a result of the increased soil pH caused by the wood ash applications.

Changes in crop productivity were monitored in plots containing wood ash applications. Increases in barley dry matter production ranging from 13 to 72% for 'AC Lacombe' barley were observed from 1998 to 2000, while increases of 27 to 65% were observed for the dry matter production of 'Harrington' barley from 1999 to 2000. Similar results were found for increases in barley grain and canola oilseed yield during the study. From 1998 to 1999 increases in 'AC Lacombe' grain yields up to 50% were observed while, 'Harrington' barley grain yields were increased up to 40% and 'Maverick' canola oilseed yield increases ranged from 2 to 98%. Dry matter production and seed yield increased with increasing rates of wood ash, with greater productivity observed in nitrogen – ash amended plots than those in plots containing only applications of wood ash. Over the last two years of the study, plots containing 12.5 and 25 t ha$^{-1}$ produced the greatest increases in dry matter and seed yield. However, there was no significant difference in seed yield between these two application rates of ash.

Levels of B and Zn were within marginal to sufficient ranges for feed. Analysis for Cd, in barley grain and oilseed samples taken from the control and 25 t ha$^{-1}$ ash treatments were below the detection limit of 0.08 mg kg$^{-1}$. This is significant if a Cd limit of 0.1 mg kg$^{-1}$, is placed on grain and oilseed traded in international markets. All the barley tissue samples, barley grain, and oilseed collected from the 6 and 12.5 t ha$^{-1}$ ash treatments were below the detection limit of 1.0 mg kg$^{-1}$ for Cd. Barley tissue and grain analysis showed elevated levels of Fe, K, and S while B, Mg, Mn, N, and P were often lower in samples taken from plots containing ash applications. Analysis of 'Maverick' oilseed showed samples taken from ash amended plots had elevated levels of nitrogen (N), manganese (Mn), S, and Zn while K was often lower in these same samples.

The content of oil, protein, chlorophyll, and glucosinolate are important in the quality of canola oilseed. Glucosinolates, found at high levels in the oilseed can restrict its use for animal feed, even if high protein levels are present. The chemical composition, specifically B, S, and Zn, of wood ash has the potential to affect all these traits. Results showed significant increases in oil content in 1998 and significant increases in protein content in 1999 and 2000 in samples taken from wood ash treated plots. This was supported by the inverse relationship that exists between oil and protein within oilseed tissue. Chlorophyll content of the oilseed increased over the three years the study was conducted. This increase paralleled an increase in B and Zn that occurred during this period also. Both B and Zn affect chlorophyll content of oilseed tissue; Zn is required for the production of chlorophyll within plant tissue. Wood ash applications significantly increased glucosinolate content from 1998 to 2000. However, levels remained below the allowable limits under the Canadian definition of 30 $\mu$mol $g^{-1}$ for canola meal for *Brassica* species.

There were no environmental or agronomic concerns resulting from the application of wood ash at rates <25 t $ha^{-1}$. Results for dry matter production, seed yield, and elemental uptake indicated that applications of 12.5 t $ha^{-1}$ provided the greatest overall benefit. There was also an indication that wood ash can provide a supplemental source of various nutrients like B, Fe, K, S, and Zn while serving as an alternative to agricultural lime.

# ACKNOWLEDGEMENTS

I would formally like to thank Alberta – Pacific Forest Industries for funding this research project and giving me this opportunity. I would also like to acknowledge the Natural Sciences and Engineering Research Council (NSERC) of Canada for the Post Industrial Scholarship I was awarded for this project.

I would like to thank my supervisors Dr. Surya Acharya of the Lethbridge Research Centre, Dr. Jim Thomas and Dr. Kevin Smith of the University of Lethbridge for the advice and support they have given me during this project.

To my parents, friends, and finally Al and Shelley Bertschi thank you for your friendship and guidance in keeping me focused, to all of you I am truly grateful.

I would also like to acknowledge the team members of Alberta – Pacific and following people and organizations that made contributions to my research.

Alberta Environment, Edmonton, Alberta

The University of Lethbridge, Lethbridge, Alberta

Erin Sullivan, SilvAgro Environmental Ltd., Sherwood Park, Alberta

EnviroTest Laboratories, Calgary, Alberta

Gateway Research Organization (GRO), Westlock, Alberta

Grain Research Laboratory, Winnipeg, Manitoba

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## LIST OF ABBREVIATIONS

Al = Aluminum

Al – Pac = Alberta – Pacific Forest Industries Inc.

As = Arsenic

Ash = Wood Ash

$B_{HWS}$ = Hot Water Soluble Boron

CCME = Canadian Council of Ministers for the Environment

Ca = Calcium

$CaCO_3$ = Calcium carbonate

Cd = Cadmium

Cogeneration = Simultaneous generation of heat, steam, and electricity as a result of the combustion of biomass or fossil fuels (Suncor Energy, 1999)

Cr = Chromium

Cu = Copper

CEC = Cation Exchange Capacity

De–ionized water = Water with negative ions removed to reduce electrical conductivity

EC = Electrical Conductivity

Fe = Iron

Fertilized Plots = Treatments containing nitrogen fertilizer

Fly ash = Coal ash

g = Gram

ha = Hectare (10, 000-$m^2$)

Hg = Mercury

kg = Kilogram

MAP = Monoammonium Phosphate

Mn = Manganese

m = metre

Mg = Magnesium

mg = Milligram

N = Nitrogen

NE = Northeast

N – fertilizer = Nitrogen fertilizer (46-0-0)

Nitrogen – ash = Plots containing nitrogen fertilizer and wood ash

NW = Northwest

Pb = Lead

ppm = Parts per million

Se = Selenium

SE = Southeast

SW = Southwest

SE22 = SE1/4 22-68-19W4th

SAR = Sodium Adsorption Ratio

t = metric tonne (1 tonne = 1000 kg)

t ha$^{-1}$ = tonne per hectare

Unfertilized Plots = Treatments not containing nitrogen fertilizer.

Zn = Zinc

## LIST OF AGRICULTURAL CROPS USED IN WOOD ASH STUDIES

**Alfalfa (*Medicago sativa* L.):**

Naylor and Schmidt, 1989

Meyers and Kopecky, 1998

cv. 'Peace' (Lickacz et al., 1998)

**Barley (*Hordeum vulgare* L.):**

(Meyers and Kopecky, 1998)

cv. 'AC Lacombe' (*Used in this study)

cv. 'Harrington' (Bertschi, 2000; *Used in this study);

cv. 'Johnson' (Lickacz et al., 1998)

**Beans (*Phaseolus vulgaris* L.):**

cv. ' Provider'; (Lerner and Utzinger, 1986);

cv. ' Harvester' (Lerner, 1983); cv. ' Blue Lake' (Etiegni, 1990; Etiegni et al., 1991);

cv. 'Blue Pole' (Krejsl and Scanlon, 1996)

**Canola (******Brassica rapa* L.):**

cv. 'Maverick' (*Used in this study)

**Corn (*Zea mays* L.):**

(Erich, 1991)

**Dallisgrass-fescue (*Paspalum dilatatum Poir. – Festuca arudinacea* Schreb.):**

(Muse and Mitchell, 1995)

**Red Clover (*Trifolium pratense* L.):**

(Muse and Mitchell, 1995)

**Oats (*Avena sativa* L. var. '501'):**

(Krejsl and Scanlon, 1996)

**Spinach (*Spinacia oleracea* L. 'America'):**

(Clapham and Zibilske, 1992)

**Wheat (*Triticum aestivum* L.):**

(Etiegni et al., 1991a; Huang et al., 1993)

# *CHAPTER ONE: WOOD ASH LAND APPLICATION*

## 1. WOOD ASH AS A SOIL AMENDMENT FOR AGRICULTURAL USE

### 1.1. Introduction

Alternative methods for disposing industrial or other types of waste products with increasing focus placed on methods with minimal environmental impact are constantly being sought; land application is considered one alternative (Campbell, 1990; Vance, 1996; Cameron et al., 1997; Mitchell and Black, 1997). Studies have shown that the land application of municipal and industrial by-products (eg. wood ash, effluents, and biosolids) can be done while posing little or no risk to the environment (Campbell, 1990; Vance, 1996; Mitchell and Black, 1997).

Companies with wood or biomass-burning facilities are looking at alternative and more sustainable methods of disposal for nearly 110, 000 tonnes (t) of wood ash produced annually in Alberta. Alberta-Pacific Forest Industries, Inc. (Al-Pac) operates a Kraft pulp mill near Boyle, AB, generating about 16, 000 t or 35, 000 cubic metres ($m^3$) of wood ash annually. Al-Pac is interested in diverting the wood ash away from the landfill utilizing it instead in a soil enhancement program involving land application of wood ash to surrounding agricultural lands, as the ash comprises approximately 45 to 50% of the waste landfilled. Initially a greenhouse study was conducted in 1996 (Bertschi, 2000), to determine the effect of wood ash on selected agricultural soils. The present study builds on the foundation of that greenhouse study.

### 1.2. Background

Wood ash has been produced for years, through the incineration of wood and wood by-products (bark, knots, waste wood) by homeowners to heat homes, and by farmers during clearing of forested lands to expand agricultural production. The ash is then disposed of by spreading on home gardens or incorporation during site preparations for agricultural production.

Farmers have historically applied ash as a result of burning fields to remove stubble or destroy weeds.

Traditionally, industrially produced wood ash has been disposed of in large landfills constructed nearby the mills; nearly 90% of the wood ash produced in the U.S. is landfilled with only 10% being land applied (Campbell, 1990). Canadian industries producing electricity through the combustion of wood waste are faced with a similar dilemma. Pulp and paper mills are relying less and less on external supplies of energy as a result of cogeneration technology, and increasing energy costs. Excess wood waste or hog fuel consisting of bark and knots is burnt to produce the electricity required for many of the production processes used in these mills. As a result, these facilities produce large volumes of wood ash on an annual basis, which must be disposed of. In recent years, costs of landfill construction, maintenance, and regulatory guidelines have made landfilling industrial wastes very costly. Mills involved in the forestry sector have begun to look for alternative means to dispose of by–products like wood ash. Land application would be a cost effective alternative for these mills. This would allow wood ash to be diverted from landfills to soil enhancement or land application programs provided operations do not have negative effects on the environment or do not exceed environmental guidelines.

Agronomic benefits resulting from the land application of pulp and paper mill by-products, such as those produced by the mill in this study have been widely studied in both Europe and the United States as soil amendments for crop production (Vance, 1996; Mitchell and Black, 1997). After applications of wood ash, increased yield, biomass and nutrient quality have been observed in many crops such as oats (*Avena sativa* L.), beans (*Phaseolus vulgaris* L.), wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), barley (*Hordeum vulgare* L.), and alfalfa (*Medicago sativa* L.); some research results and references for these are presented in Table 1. Soils where ash had been placed have shown increases in productivity for several years afterwards (Hopkins, 1910; Karsisto, 1979; Vance, 1996).

**Table 1. Summary of published research involving wood ash applications modified from Mitchell and Black (1997).**

| *Research Topic(s):* | *Application Rate(s)* | *(G)reenhouse / (F)ield Study* | *Research Results* | *Reference* |
|---|---|---|---|---|
| Soil Chemistry | 0 to 35.9 t ha$^{-1}$ | G | Increased soil pH; Increased soil Ca, K, and P | Naylor and Schmidt, 1986 |
| Alfalfa; Soil Quality | 0 to 50 t ha$^{-1}$ | F | Ash increased soil pH; exchangeable K and Mn; decreased exchangeable Al and Fe; increased hay yield and quality; No detrimental effect to crop or soils; Problem with excessive rates. | Naylor and Schmidt, 1989 |
| Wheat & Poplar Trees | 0 to 30% of soil mass | G | No detrimental effects and increased biomass at rates <2%; Recommend use of ash as lime or nutrient source; Problems at rates >2% | Etiegni et al., 1991a |
| Bush beans | 10 t ha$^{-1}$ | G | Limiting factors are pH and K; Application rate of ash should be based on CCE; Reduced yields in beans at pH>6.5 or >2.66 t ha$^{-1}$ | Etiegni et al., 1991b |
| Corn | Based on P or K | G | Effective source of P and K | Erich, 1991 |
| Wheat | 0 to 36 t ha$^{-1}$ | F | No effect on growth or protein; No significant uptake of heavy metals; increased soil pH | Huang et al., 1992 |
| Soil Chemistry | Incubation Study | G | Release of P and K; high solubility of wood ash K | Ohno, 1992 |
| Spinach | 0 to 4.06 g kg$^{-1}$ (dry weight basis) | G | Increased soil pH and EC | Clapham and Zibilske, 1992 |
| Pasture; Soil Chemistry | 4.5 and 9.0 t ha$^{-1}$ | F | Increased soil pH and forage yield greater than equivalent lime rate; No effect on quality | Muse and Mitchell, 1995 |
| Field and column leaching study | 11 to 44 t ha$^{-1}$ |  | Increased soil cations; no adverse effect on groundwater | Williams, Hollis, and Smith, 1995 |
| Oat and Bean | 0 to 50 t ha$^{-1}$ | G | Increased biomass compared to lime; Increased uptake of P, S, and B in oats; Increased uptake of K, S, and B in Beans; Yield decreases observed in oats at higher rates. | Krejsl and Scanlon, 1996 |
| Alfalfa, Barley, Soil Chemistry | 0 to 89.6 t ha$^{-1}$ | G and F | Increased yields in alfalfa and barley relative to controls; Growth response not dependant on ash source; Minimal effect on elemental composition of plant tissue | Meyers and Kopecky, 1998 |

**Table 2. Chemical characteristics of wood ash used in this study and other wood ashes used in published studies**

| | ----% ---- | | | | | | | | | | ---- $mg\ kg^{-1}$ ---- | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Source †* | *pH* | *$CaCO_3$ Equiv.* | *Al* | *Ca* | *K* | *P* | *$SO_4$* | *Mg* | *Mn* | *Na* | *B* | *Cd* | *Cu* | *Hg* | *Ni* | *Pb* | *Zn* |
| Al – Pac Wood Ash | 13.1 | 52.0 | 0.7 | 21.1 | 3.3 | 0.6 | 1.7 | 1.9 | 0.06 | 1.6 | 121 | 11.7 | 53.3 | 0.2 | 17.0 | 36.1 | 1504 |
| Ash 1 | 12.7 | n/a | 1.6 | 27.0 | 3.1 | 0.8 | n/a | 1.6 | 1.3 | 0.3 | n/a | 7.9 | 90.3 | n/a | 49.1 | 72.2 | 381 |
| Ash 2 | 12.4 | n/a | 1.2 | 14.7 | 2.4 | 0.6 | n/a | 1.0 | 0.7 | 0.2 | n/a | 6.0 | 61.7 | n/a | 43.0 | 51.1 | 232 |
| Ash 3 | 12.3 | n/a | 1.3 | 13.2 | 2.8 | 0.4 | n/a | 0.9 | 0.8 | 0.3 | n/a | 6.3 | 78.7 | n/a | 30.6 | 53.1 | 316 |
| *Ash 4* | 12.1 | n/a | 1.5 | 32.1 | 11 | 1.1 | n/a | 2.5 | 0.8 | 0.5 | n/a | 2.2 | 180 | n/a | 56.6 | 67.1 | 1250 |
| *Ash 5* | 12.7 | n/a | 1.1 | 28.1 | 13 | 1.3 | n/a | 2.1 | 0.7 | 0.4 | n/a | 2.5 | 146 | n/a | 58.2 | 44.2 | 507 |
| Ash 6 | 11.9 | 35 | 1.6 | 12.8 | 1.7 | 0.3 | n/a | 0.8 | 0.7 | 0.2 | n/a | 4.2 | 40 | <0.1 | 11.6 | 38 | 200 |
| Ash 7 | 13.1 | 92.4 | 2.4 | 33.1 | 4.2 | 1.4 | 0.4 | 2.2 | 0.7 | 0.3 | 8.4 | 26.3 | 140.8 | n/a | 50.6 | 127.2 | 691.6 |
| *Ash 8* | 13.3 | 91.2 | 2.3 | 30.3 | 4.1 | 1.4 | 0.5 | 2.3 | 0.7 | 0.4 | 7.7 | 15.3 | 148.4 | n/a | 43.0 | 133.0 | 709.0 |
| *Ash 9* | 12.9 | 35.7 | 1.3 | 10.9 | 2.9 | 0.7 | 0.7 | 1.6 | 0.3 | 0.2 | 127 | 3 | 78 | <4.9 | 12.0 | 66.0 | 794 |
| *Ash 10* | 9.9 | 37.5 | 1.2 | 12 | 1.3 | 0.3 | <0.01 | 0.8 | 0.3 | 0.1 | 95.2 | 1.5 | 66.8 | n/a | 15.8 | 72 | 183 |
| *Ash 11* | 11.9 | 40 | 0.4 | 12.1 | 1.0 | 0.3 | n/a | 2.1 | 0.3 | 0.07 | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| *Ash 12* | 12.2 | 54 | 0.7 | 20.0 | 2.0 | 0.6 | n/a | 3.1 | 0.5 | 0.2 | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| *Ash 13* | 12.1 | 29.1 | n/a | 6.5 | 0.6 | 0.3 | 0.02 | 0.9 | 0.07 | 0.6 | 200 | 2 | 107 | 0.3 | 26 | 20 | 134 |
| *Ash 14* | | 103 | 0.5 | 31.9 | 2.3 | 0.6 | n/a | 1.6 | 0.1 | n/a | 156 | 3.7 | 40.4 | n/a | 4.3 | 4.5 | 840 |
| *Ash 15* | 11-12 | 73 | 1.1 | 23.5 | 3.7 | 0.6 | n/a | 1.6 | 0.1 | n/a | 193 | 22 | 49.0 | n/a | 6.3 | 8.2 | 3000 |
| *Ash 16* | | 96 | 1.1 | 22.0 | 1.5 | 0.6 | n/a | 1.4 | 0.2 | n/a | 25 | < | < | n/a | < | < | 1150 |
| *Fertilizer* | 9.2 | | 0.0 | 0.04 | 45.1 | 0.05 | n/a | 0.1 | 5.0 | 1.4 | n/a | 0.2 | 2.0 | n/a | 10.0 | 21.0 | 2.0 |
| *$CaCO_3$ - 1* | 9.9 | 100 | 0.2 | 31.4 | 0.1 | 0.06 | n/a | 5.1 | 0.05 | 0.07 | n/a | 0.7 | 10 | n/a | 20 | 55 | 113 |
| *$CaCO_3$ - 2* | 10 | n/a | 0.2 | 30.0 | 0.1 | 0.06 | n/a | 5.0 | 0.05 | n/a | n/a | n/a | n/a | n/a | n/a | n/a | n/a |
| *CaO – 3* | 12.5 | 99.9 | 0.3 | 55.4 | 0.1 | 0.05 | n/a | 0.8 | <0.01 | 0.05 | n/a | 0.2 | 12.0 | n/a | 34.0 | 45.1 | 4.0 |

† Source: Ash 1 – 5, Fertilizer – KCl; Limestone: $CaCO_3$ – 1, CaO (Naylor and Schmidt, 1986); Ash 6 (Naylor and Schmidt, 1989); Ash 7-8 (Etiegni et al., 1991a); Ash 9 (Huang et al., 1993); Ash 10 (Muse and Mitchell, 1995); Ash 11 – 12, Limestone: $CaCO_3$ – 2 (Kahl et al., 1996); Ash 13 (Krejsl and Scanlon, 1996); Ash 14 - 16 (Meyers and Kopecky, 1998); n/a Not available; < Below detection limit

Increases in agricultural production following ash application have been attributed to the chemical composition of the wood ash and effect on soil chemistry, such as increased soil pH and the addition of elements essential for plant growth (i.e. B, Ca, Fe, K, Mg, P, S, and Zn) (Naylor and Schmidt, 1989; Etiegni et al., 1991a; Muse and Mitchell, 1995; Vance, 1996; Meyers and Kopecky, 1998). Campbell (1990) indicated the chemical content of the ash (i.e. the residual left after combustion) is highly variable in different deciduous and coniferous tree species, influenced by both soil type and climate. According to this author the chemical content is also highly influenced by the combustion system and handling of the wood prior to incineration. Hatch and Pepin (1985) suggest that four tonnes of ash is equivalent to one tonne of agricultural limestone; this would vary depending upon the $CaCO_3$ equivalence of the ash. Selected chemical characteristics of wood ash produced by Alberta – Pacific and ash used in other research studies are presented in Table 2.

In addition to essential macro- and micronutrients, wood ash also contains low to moderate levels of trace elements and heavy metals like B, Cd, and Zn. Someshwar (1996) states that wood ashes tend to be higher in Ca, K, and Mn but lower in aluminium (Al), arsenic (As), chromium (Cr), Fe, mercury (Hg), and selenium (Se) than coal ashes and levels of dioxins, furans, and polyaromatic hydrocarbons are strongly dependent on the chemical composition of the fuel source. High levels of dioxins and furans are often associated with mills burning salt laden wood residue or wood fuel with a high chloride content (Someshwar, 1996). Wood ashes from coastal mills often have higher chloride levels due to salt water than inland mills (Campbell 1990; Someshwar, 1996). Ohno (1992) stated contamination of surface water after immediate incorporation of ash after land application would be minimal, however the risk of P contamination remains from surface runoff containing unincorporated ash. A literature search produced no published reports of metals contained within the ash being an environmental, crop quality or crop productivity concern provided the ash is applied as a liming alternative at rates considered for use agronomically (<50 t $ha^{-1}$); this was supported by Mitchell and Black (1997). Ash produced by the mill in this study has similar characteristics to ash used in previous studies, and should benefit crop production by acting as a liming agent as well as a possible source of nutrients.

### 1.3. Guidelines for the Land Application of Wood Ash

Application of wood ash to agricultural lands is rapidly expanding with various industrial operations burning wood and biomass to produce energy. Land application of industrial waste by-products such as lime, combined biosolids, and wood ash is controlled through regulations currently established for other industries by Canadian Council of Ministers for the Environment (CCME) and Alberta Tier–1 Criteria for Contaminated Assessment and Remediation. Currently there are no specific guidelines in Canada regulating land application of wood ash. However, Alberta Environment (AE) in association with industries in Alberta operating cogeneration facilities is establishing guidelines to regulate the land application of wood ash within the province of Alberta.

Alberta Environment, in developing these guidelines, outlined various parameters that were of concern when using wood ash in a land application program. These included soil pH, electrical conductivity (EC), sodium adsorption ratio (SAR), hot water soluble B ($B_{HWS}$), cadmium (Cd), zinc (Zn) and the accumulation by plant tissue of B, Cd and Zn. The earlier greenhouse study (Bertschi, 2000) found SAR not to be significantly affected by ash applications and therefore, was not evaluated during the field study. Soil pH, EC, $B_{HWS}$, Cd and Zn will play a significant role in determining sustainable agronomic rates for the application of wood ash, and may influence restrictions imposed in the future due to the accumulation within the soil. One of the objectives of this field study was to determine rates that could be used for application and not infringe on existing environmental regulations.

### *1.3.1. Soil pH and EC*

The high alkalinity (pH = 13) and electrical conductivity (EC = 50.3 dS $m^{-1}$) of the wood ash used in this study posed concerns around the land application of this material. Alberta Environment has traditionally taken the position to limit and regulate the land application of material that will only show agronomic benefit and enhance the properties of the receiving soils. Soil pH plays a significant role in the solubility of nutrients and metals within the soil profile (Wolf, 1990). Acidic soils with low pH can result in toxic levels of $Al^{+3}$, $Mn^{+2}$, and several heavy metals including B and Cd. Increasing soil pH leads to low availability of these elements, while increasing the availability of many macronutrients like K, P, and S in addition to micronutrients like Zn can result in increased crop productivity. As a result Alberta Environment has regulated soil pH, placing an upper limit of 8.5 (0.01M $CaCl_2$) on soils through the Alberta Tier – 1 Guidelines for Contaminated Sites (Alberta Environment, 1994).

Soil EC is also important in crop productivity; dissolved salts (cations and anions) play an important role in nutrient and water regulation within the soil profile, influencing nutrient uptake (Wolf, 1990). In particular, compounds such as $Na^+$, $Cl^-$, $HCO_3^-$, $SO_4^{-2}$, and $HBO_3^-$ have been recognized as important (Wolf, 1990). Soil EC depends on the concentration of these ions in solution and their ability to conduct electricity; soil with an EC > 2 dS $m^{-1}$ is considered to be saline and would be unsuitable for ash application (Alberta Environment, 1994). Alberta Environment regulates soil EC by placing an upper limit of 2.0 dS $m^{-1}$ for soil EC through the Alberta Tier – 1 Guidelines for Contaminated Sites (Alberta Environment, 1994).

### *1.3.2. Boron*

Boron is one of the elements Alberta Environment has expressed concern with regarding the land application of wood ash, because the concentration in the ash (Table 2) exceeds that normally found in soils of Alberta (Alberta Agriculture, 1992). Boron if often deficient in canola and alfalfa grown in Luvisolic soils these deficiencies can be overcome through the addition of micronutrient fertilizers (Alberta Agriculture, 1992). Various studies involving agricultural applications of coal ash, municipal, and industrial biosolids indicated these products could be used safely to increase $B_{HWS}$ levels within deficient soils. Applications of these products at high rates may lead to B toxicity in agricultural crops (Gupta et al., 1976; Kukier et al., 1994). Alberta Environment has placed upper limits of 2.0 mg $kg^{-1}$ on $B_{HWS}$ through Alberta Tier – 1 Guidelines (Alberta Environment, 1994).

### *1.3.3. Cadmium*

Cadmium is a heavy metal that poses many environmental and health concerns due to its ability to bioaccumulate within plant, animal, and human tissue (Chaudhary et al., 1994; Grant et al., 1998). Agricultural practices such as fertilization can result in significant additions of Cd to soil; Cd levels up to 480 mg Cd $kg^{-1}$ have been found in fertilizer (Grant and Bailey, 1998). A study by Raven and Loeppert (1997) suggests phosphate rock had higher levels of trace elements and heavy metals than sewage sludge and phosphate fertilizers. Raven and Loeppert (1997) also indicated that phosphate fertilizers had higher levels of these compounds than organic amendments, liming materials, as well as K and N fertilizers. Wood ash Cd content is quite variable and concentrations up to 28.8 mg $kg^{-1}$ have been observed (Table 2). These levels are comparable to those found in agricultural materials such as calcite, compost, diammonium phosphate, manure, rock phosphate, and urea that have concentrations of <0.2 to 48.8 μg Cd $g^{-1}$ (Table 5: Raven and Loeppert, 1997). Upwards of 130 mg $kg^{-1}$ can be found in phosphate rock (Mortvedt, 1987), 80 mg $kg^{-1}$ in monoammonium phosphate (MAP), and 480 mg $kg^{-1}$ in $ZnSO_4$ fertilizers have been observed (Grant and Bailey, 1998). The solubility of Cd within the soil is reduced when soil pH is less than 6.5. Studies have indicated liming soils to a pH near 7 greatly affects the solubility of Cd, reducing its availability for plant uptake (Pepper et al., 1983; Wolf, 1990; Grant et al., 1998). Wood ash application would increase soil pH in acidic soils reducing Cd availability, but would also increase the pool of Cd within the soil. Alberta Environment has placed an upper limit of 1.0 mg Cd $kg^{-1}$ within the soil under Alberta Tier – 1 Guidelines for Contaminated Sites (Alberta Environment, 1994).

### *1.3.4. Zinc*

Zinc, another heavy metal, is closely regulated by Alberta Environment. Alberta Tier – 1 Guidelines identify an upper limit for Zn in soil of 120 mg $kg^{-1}$ in Alberta (Alberta Environment, 1994). Zinc concentrations in wood ash are quite variable with levels of 3300 mg $kg^{-1}$ being observed (Table 2). Agricultural crops vary in their tolerance and requirement for Zn within the soil and availability decreases with increasing soil pH (Wolf, 1990). Zinc plays an important role in the production of chlorophyll in plant tissue and function of many plant enzymes and hormones (Salisbury and Ross, 1992).

## 1.4. Justification for Research

Although numerous published studies are present in the literature pertaining to application of wood ash to agricultural soils, these have been conducted mainly in the United States and Europe (Karsisto, 1979; Vance, 1996; Mitchell and Black, 1997). Few studies have been conducted on Canadian soils where the effect of applications of wood ash on plant productivity and soil chemistry was evaluated. Various research projects in Alberta, such as this field study and other work by Lickacz et al. (1998) and Bertschi (2000) addressed these issues. Bertschi (2000) stated initially "Alberta Environment regulators were reluctant to approve wood ash as a soil amendment due to the lack of research on Canadian soils and the need to demonstrate benefits resulting from its application".

### 1.5. Results from the Initial Greenhouse Study

In 1996, a greenhouse study was initiated to begin evaluating the effects of wood ash as a soil amendment for agricultural and silvicultural use in Alberta, while addressing the concerns of Alberta Environment. The initial study was conducted to assess the effects of ten different loading rates on the growth of barley (*Hordeum vulgare* L. cv. 'Harrington') and poplar cuttings (*Populus deltoides* cv. 'Assiniboine') in an effort to determine loading rates suitable for field studies. Ten loading rates ranging from 0 t ha$^{-1}$ (control) up to 200 t ha$^{-1}$ of wood ash were applied to two different soil types in this study; i.e. to Eluviated Dystric Brunisols and Orthic Gray Luvisols commonly found in the area surrounding the Al – Pac mill site near Athabasca, Alberta, Canada (Bertschi, 2000).

In the greenhouse study significant increases in barley biomass were observed in all the ash applications up to 200 t ha$^{-1}$ in both soil types with the exception of the 200 t ha$^{-1}$ treatment in the Brunisolic soil (Bertschi, 2000). Soil pH in the greenhouse study increased 24-hrs after application and levels began to level out after 30-days where they remained relatively constant and below Alberta Tier – 1 Guidelines. $B_{HWS}$ and total Zn levels in ash treatments were significantly higher, than controls, but remained below Alberta Tier – 1 Guidelines. SAR was not a concern in wood ash applications up to 60 t ha$^{-1}$. Analysis of barley tissue collected at day 70 from rates up to 60 t ha$^{-1}$ found significant increases in B and Zn but no significant differences in Cd uptake compared to unamended soils. Analysis of barley grain samples indicated a significant uptake in B only in the 60 t ha$^{-1}$ treatment. Significant uptake in Cd only occurred in the 40 and 60 t ha$^{-1}$ treatments while Zn uptake was significantly increased in all treatments. Wood ash applications resulted in significant increases in plant production and increased elemental uptake, providing the background data necessary for determining potential application rates in this field study.

Greenhouse studies provide controllable conditions to reduce environmental variability, however, their scope is limited as they provide little information as to what would be expected under field conditions. Pot studies provide a contained environment where plant roots are confined to a relatively small area and subjected to concentrated levels of wood ash higher than would be expected under field conditions. Greenhouse studies allow the individual effects of nutrients or trace metal additions on plant growth under controlled conditions minimizing the interactions of other factors, like the environment (ex. moisture, temperature, and sunlight) (Grant and Bailey, 1998). These authors indicated studies have shown patterns of Cd accumulation in crops differed between studies conducted under greenhouse (solutions with high Cd levels) conditions compared with similar field studies.

The field study was established to address the effect applications of wood ash would have on plant growth, nutrient and metal uptake by plant tissue, and changes in soil chemistry under field conditions. Two criteria were used to determine rates used in this field study. The first was based on results from the initial greenhouse trial outlined above and rates used in other literature studies, the second was determined by rates considered to be economical and sustainable for site enhancement.

### 1.6. Objective

The objective of the present field study was to determine wood ash application rates that would have minimal environmental impact while still providing benefits to crop growth. The specific objectives of the study were:

1. To assess effects of wood ash applications on crop productivity (dry matter production, seed yield, and crop quality).
2. To determine the effect of wood ash applications on a Luvisolic soil in Central Alberta, specifically nutrient availability and heavy metal loading.
3. To determine if wood ash can act as a potential liming amendment and nutrient supplement.
4. To evaluate the duration of effectiveness of wood ash applications under field conditions.
5. To determine if wood ash in combination with nitrogen fertilizer would increase plant productivity.
6. To determine wood ash application rates that could be applied using conventional farm equipment to improve the growth of agricultural crops, while not exceeding any of Alberta's site contamination criteria.

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*CHAPTER TWO: SOIL RESPONSE TO WOOD ASH*

## 2. EFFECT OF WOOD ASH APPLICATION ON THE CHEMICAL AND PHYSICAL PROPERTIES OF A LUVISOLIC SOIL FROM THE CENTRAL ALBERTA REGION, NEAR BOYLE ALBERTA

### 2.1. Introduction

In recent years, companies from the forest sector have focused on developing sustainable options for disposing their waste by-products. Land application of by-products such as wood ash, is becoming a more appealing alterative. Companies have initiated research programs evaluating the effects of the application of wood waste, wood ash, biosolids, and lime on plant growth, nutrient uptake, and soil chemistry. Wood ash is potentially the most beneficial by-product produced, providing numerous benefits when applied to agricultural or forest soils.

The liming potential (i.e. ability to increase soil pH) and elemental content (i.e. B, Ca, K, Mg, P, S, and Zn) of wood ash would provide benefits essential for plant growth on acidic (low pH) or nutrient deficient soils. Different soils also have a capability to resist changes in pH through the soil's buffering capacity (Brady and Weil, 1999). As a result, soils with different buffering capacities require different application rates of wood ash to obtain the same change in pH. Studies evaluating the effect of wood ash application on soil pH have found minimal differences (i.e. up to 0.5 units) between ash application rates of 10 to 30 t ha$^{-1}$ (Naylor and Schmidt, 1989; Muse and Mitchell, 1995; Meyers and Kopecky, 1998). This would suggest that the soil's buffering capacity might also play a role in regulating changes in soil pH. Wood ash applications may also affect soil microflora; a study by Fritze et al. (1994) suggested applications of wood ash up to 5 t ha$^{-1}$ showed increases in microbial activity within the soil. However, the ash also contains elements that are either potentially toxic at high concentration within the soil or are at risk of bioaccumulation within animal or plant tissues. Alberta Environment was primarily concerned with the soil accumulation and plant tissue uptake of hot water soluble boron ($B_{HWS}$), cadmium (Cd), and zinc (Zn). Concerns were also raised about the effect ash applications would have on soil pH and electrical conductivity (EC) of selected soils.

Agricultural crops have varying degrees of tolerances to soil pH. Crops such as clover, corn, grasses and oats perform well at a pH around 6.2; barley and wheat prefer a pH around 6.5, while alfalfa and soybeans prefer a pH around 7.0 (Wolf, 1990; Brady and Weil, 1999). The effect of agronomic applications of wood ash (<50 t $ha^{-1}$) on soil pH has been well studied in Europe and the United States (Vance, 1996; Mitchell and Black, 1997). Increases in soil pH ranging from 0.5 to 1.5 units have been observed in these studies (Naylor and Schmidt, 1986; Naylor and Schmidt, 1989; Muse and Mitchell, 1995; Meyers and Kopecky, 1998). Wood ash used in these studies had calcium carbonate ($CaCO_3$) equivalents less than that of agricultural lime. Hatch and Pepin (1985) suggested four tonnes of ash are equivalent to one tonne of agricultural limestone; this would vary depending upon the $CaCO_3$ equivalence of the ash. Clapham and Zibilske (1992) suggested wood ash may react faster than limestone but lasts only a short duration; agricultural lime may be used as a supplement to increase soil pH for a longer term. However, long - term effects on soil pH have also been found as a result of wood ash applications (Naylor and Schmidt, 1989; Muse and Mitchell, 1995).

Studies have indicated that wood ash, while serving as a suitable alternative to agricultural lime, has the benefit of providing various micronutrients, like B and Zn, as well as macronutrients, such as Ca, Mg, K, P, and S essential for plant growth (Naylor and Schmidt, 1989; Ohno and Erich, 1990; Muse and Mitchell, 1995; Meyers and Kopecky, 1998). Naylor and Schmidt (1989) showed applications of ash increased soil pH, increased exchangeable K, Ca, Mn, and Mg and decreased exchangeable aluminium and Fe within the soil. Muse and Mitchell (1995) found ash applications increased extractable levels of Ca, Mg, K, P, and Na. Ohno and Erich (1990) found wood ash supplied moderate amounts of P and K to soil, but no relationship between P released during the incubation of wood ash within the soil profile and the soil pH was found. The authors suggested reactions of P in the soil largely determine the availability of P. The addition of P to soil in recent years has become a concern. Ohno (1992) states that contamination of surface water after application and immediate incorporation of wood ash is minimal, however, a P contamination risk remains for unincorporated ash from surface runoff.

Wood ashes also contain low to moderate levels of trace elements and heavy metals such as B, Cd, and Zn that at high concentrations can accumulate within plant, animal, and human tissues. However, a literature search, supported by Mitchell and Black (1997), found no published reports of environmental, crop production, or crop quality problems provided the ash was applied as an alternative to an agricultural liming material. At higher application rates of ash, toxicity symptoms have been observed, however, these rates are too high to be considered for agricultural use (Etiegni et al., 1991b). Mitchell and Black (1997) state stricter regulations on private, public, and industrial landfills have resulted in a significant effort to divert selected waste by-products to alternative methods of waste disposal. This has resulted in land application programs becoming more appealing, however, these authors indicated that certain criteria must be addressed before land application of wood ash can be considered a viable alternative. These criteria included: the value of ash, logistics of application, environmentally harmful properties, and public objections.

### 2.2. Objective

The focus of this research project was to evaluate the effect of wood ash applications, under field conditions, on the Luvisolic soils of Central Alberta. The focus was to evaluate wood ash application rates based on economic considerations and results from a previous greenhouse study (Bertschi, 2000). The goal was to determine if selected rates would have beneficial or deleterious effects on the selected soils, by evaluating soil pH, EC, nutrient and metal accumulation. The main objectives for this portion of the field study were:

1. To determine the effect of wood ash applications on the properties of a Luvisolic soil under field conditions in Central Alberta.
2. To evaluate the efficacy and duration of single applications of wood ash on increasing soil pH, nutrient, and heavy metal availability with specific focus placed on $B_{HWS}$, Cd, and Zn.

## 2.3. Methods and Materials

### *2.3.1. Study Design*

The site chosen for the study had been continuously cropped before the study began, and is located in the Luvisolic soil zone (Appendix A - Figure 6). The quarter section (SE1/4 22-68-19W4) was divided into three blocks, located in the NE, NW, and SE portion of the section (Appendix A - Figure 7). A randomized complete block design was used for the experiment, with four loading rates: 0, 6, 12.5 and 25 t $ha^{-1}$ located in each block. Replications (blocks) were located in the NW and SE area of the quarter; plots were 50-m wide by 300-m long, whereas plots in the NE portion were 30-m wide and 250-m long. A 3-m buffer zone was used to separate the three crops and wood ash treatments used in the study. The buffer was rotovated twice during each year to a depth of 0.2-m. Each of the wood ash plots was further divided into three sections for seeding canola and two barley cultivars. Crops were seeded perpendicular to wood ash and nitrogen applications.

### *2.3.2. Ash*

Wood ash supplied by the Kraft pulp mill is produced through the incineration of wood waste, consisting of bark and knots, as fuel. The mill operates a wood and natural gas fueled power boiler producing 16, 000 t of wood ash annually. The ash has been characterized extensively for physical characteristics, available nutrients, total nutrients, available metals, and total metals (Appendix D). Wood ash was stockpiled on-site in SE1/4 22-68-19W4 prior to application from March 1998 to mid-May 1998. Ash was applied starting mid-May in 1998 using a side discharge GEHL Scavenger Manure Spreader (Appendix E) calibrated to apply wood ash at 6, 12.5 and 25 t ha$^{-1}$. Following application, the ash was incorporated, by disc, into the plow layer to a depth of 0.2-m and allowed to incubate five days before first year seeding occurred.

### *2.3.3. Soils*

The site of the field trial was located near the Kraft pulp mill operated by Alberta- Pacific Forest Industries Inc. at SE1/4 22-68-19W4, near Boyle, AB, in Orthic Gray Luvisol soils (Appendix A - Figure 6). The site is complex in nature with a classification of 80% Tolman, 10% Tawatinaw, and 10% Amisk soils with a gently undulating slope of 2-4% (Report No. 29, 1972). Amisk soil groups are part of the Degraded Brunisols, while; both the Tolman and Tawatinaw groups belong to the Orthic Gray Luvisols. The soil horizons are Ae, Bt, and Ck with a silt loam texture and moderately acidic soil pH from 5.5 to 6 (Report No. 29, 1972). The main soil group, or Tolman soils, have developed on alluvial lacustrine well-drained parent material under forest vegetation of primarily hardwood species such as aspen, poplar, and white birch (Report No. 29, 1972).

In May and October of each year soil samples (n=6) were collected to a depth of 0.2-m and analyzed for nutrients and trace metals. Each sample consisted of 10 random sub - samples taken from each of the 'AC Lacombe' barley and 'Maverick' canola plots for each of the three replications. Soil samples sent for chemical analysis were only collected from the treatments containing the additional nitrogen fertilizer. These samples were sent to EnviroTest Laboratories

(Calgary, AB) each year for analysis. Samples were dried at 40°C and ground using a flail type grinder to pass through a 2-mm sieve. Ground samples were then analyzed for N, P, K, S, B, Cd, Cu, Fe, Mn, and Zn. A shake extraction was used for N and S analysis, using de-ionized water and $CaCl_2$; the soluble $NO_3$, $NO_2$, and $SO_4$ were collected and analyzed using a Technicon Autoanalyzer for $NO_3$ and $NO_2$ analysis, while $SO_4$-S was analyzed using ICP-AES. Analysis of P and K was done using a Modified Kelowna extraction ($NH_4OAc$ + NHF + HOAc); P was analyzed using a Technicon Autoanalyzer and K measured using a Flame Photometer. A DTPA extraction was used for the metals Cd, Cu, Fe, Mn, and Zn; these were then analyzed by ICP-AES. Hot water soluble B ($B_{HWS}$) was extracted in hot water (100°C for 5 minutes) and analyzed using ICP-AES.

Additional soil samples were collected throughout the study to monitor changes in soil pH and EC as a result of wood ash application. Samples (n=36) collected in May and October of each year from each of the crop areas containing the four ash treatments for all three replications, were analyzed for statistical differences. Soils were analyzed for pH in saturated pastes of de-ionized water and 0.01M $CaCl_2$ (Hendershot, Lalande, and Duquette, 1993); EC measurements were conducted in saturated pastes of de-ionized water.

### *2.3.4. Crops*

Barley and canola are valuable crops in Alberta, and are commonly grown crops in the Prairie Provinces of Canada. Barley cultivars (*H. vulgare* L.) used in this study included six-row barley 'AC Lacombe' (Kibite, 1993) commonly used for silage and feed grain and two – row barley 'Harrington' (Harvey and Rossnagel, 1984) used in malting (Appendix F: Figure 12 to Figure 13). A Polish canola (*Brassica rapa* L.) cultivar 'Maverick', was also chosen for the study because of its early maturity (Appendix F: Figure 14). All crops were fertilized and seeded in the last week of May for the three years of the study. Barley cultivars were seeded at a rate of 112 kg $ha^{-1}$ using a

John Deere Air Seeder, and the Polish canola, at a rate of 7.8 kg ha$^{-1}$ using a Valmar Airflo Seeder. Crops were seeded in the same location for all three years of the study. Half of each plot was fertilized by banding with urea (46-0-0) to provide 130 kg ha$^{-1}$ (56 kg ha$^{-1}$ 1998; 103 kg ha$^{-1}$ 1999; 108 kg ha$^{-1}$ 2000) of nitrogen based on soil fertility analysis. Weed control in 1998 in the canola was conducted using the pre-emergent herbicide Edge™ and by spraying Lontrel 360™ with Poast Ultra™ and Merge™ in early July while weed control within the barley was done using Refine Extra™ and Assert™. Similar weed control measures were used in 1999 and 2000. Due to late maturity a pre-harvest application of Round-up™ was applied in early-September of 1998 for dessication of barley and canola.

### *2.3.5. Climatic Data*

Climatic factors such as temperature and precipitation play significant roles in the development and productivity of all agricultural crops. The Athabasca region receives approximately 500-mm of total precipitation annually based on a 40-year average from 1959 to 1999 (Environment Canada data). Precipitation data (Appendix B: Table 42 & Figure 8) obtained from Environment Canada showed during the three years this study was conducted (1998 to 2000) the total annual precipitation was 32, 15, and 24% lower in 1998, 1999, and 2000 respectively than the long - term average. The average temperature from May to August during the course of the study was similar to the 40-year average for the area (Appendix B: Table 43 & Figure 9).

### *2.3.6. Statistical Analysis*

Tests to satisfy assumptions set by the ANOVA test were conducted and were supported. Analysis of variance was conducted on data collected for dry matter and grain yield using the statistical program AGROBASE™ 99 (Agronomix, 1999). Statistical differences among means were then determined using Fisher's Protected Least Significant Difference (LSD) test at P=0.05, P=0.01, P=0.001, and P=0.0001 levels.

## 2.4. Results

### *2.4.1. Soil Electrical Conductivity and pH*

Samples collected from wood ash amended soils indicated that the wood ash applications increased the pH of the Luvisolic soil. The sampling-session effect had no significant impact on soil pH or EC however, treatment and treatment-by-sampling-session interactions were found to have a significant influence on soil pH and EC (Table 3).

Average soil pH was increased by 1 to 1.2 units compared to the control after ash applications of 6 to 25 t $ha^{-1}$. Figure 1 and Table 4 show the soil pH levels of samples taken from the plots amended with ash in 1998. Soil pH changes were observed to be similar irrespective of the technique used. Soil pH continued to increase up to 80 days from application and incorporation of the wood ash (Figure 1). Soil pH levels showed annual fluctuations during the study. These naturally occur in soils due to changes in environment, moisture, and microbial activity (Tisdale and Nelson, 1975; Brady and Weil, 1999). Soil pH levels were significantly different among treatments in 1999 and 2000 with the greatest increase in pH observed in the 25 t $ha^{-1}$ treatment. However, soil pH values did not exceed 7.7 in any treatment (Figure 1 and Table 4).

Alberta Environment expressed concern about the high EC (50.3 dS $m^{-1}$) of the wood ash used in the study. Soil EC (Table 5) were significantly greater in the ash treatments in the first two years after ash applications but levels have since decreased to levels similar to that before the application of wood ash.

**Table 3. Probability of F values for soil pH and EC for treatments (Treat), N – fertilizer (Fert), soil sampling-sessions conducted in May and October (session), crop (barley and canola), and their respective interactions for soil samples collected from control and wood ash amended plots (1998 - 2000).**

| | | *SOIL pH AND EC (1998-2000)* | | |
|---|---|---|---|---|
| | | *0.01M $CaCl_2$* | *De – Ionized Water* | |
| | | *pH* | *pH* | *EC* |
| *Source* | *df* | | *Probability* | |
| *Total* | *863* | | | |
| *Rep* | *2* | **** | ** | **** |
| *Treat* | *3* | **** | **** | **** |
| *Fert* | *1* | n/s | ** | ** |
| *Session* | *5* | **** | **** | **** |
| *Crop* | *2* | n/s | n/s | n/s |
| *Treat*Fert* | *3* | n/s | * | n/s |
| *Treat*Crop* | *6* | n/s | n/s | n/s |
| *Treat*Session* | *15* | **** | **** | **** |
| *Fert*Crop* | *2* | * | * | n/s |
| *Fert*Session* | *5* | n/s | n/s | * |
| *Crop*Session* | *10* | n/s | *** | n/s |
| *Treat*Fert*Crop* | *6* | n/s | n/s | n/s |
| *Treat*Fert*Session* | *15* | n/s | n/s | n/s |
| *Treat*Crop*Session* | *30* | n/s | n/s | n/s |
| *Fert*Crop*Session* | *10* | n/s | n/s | n/s |
| *Treat*Fert*Crop*Session* | *30* | n/s | n/s | n/s |
| *Residual* | *718* | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

### *2.4.2. Soil Cadmium and Zinc*

Metals like Cd and Zn are often environmental concerns as they are found in high concentrations within manure, biosolids, coal and wood ashes. Cadmium levels within the treatments were not detected above the 1.0 mg $kg^{-1}$ detection limit for any of the treatments and so no statistical comparisons were made. Total Zn levels also did not exceed the Alberta Tier – 1 Guideline limit of 120 mg $kg^{-1}$ (data not shown).

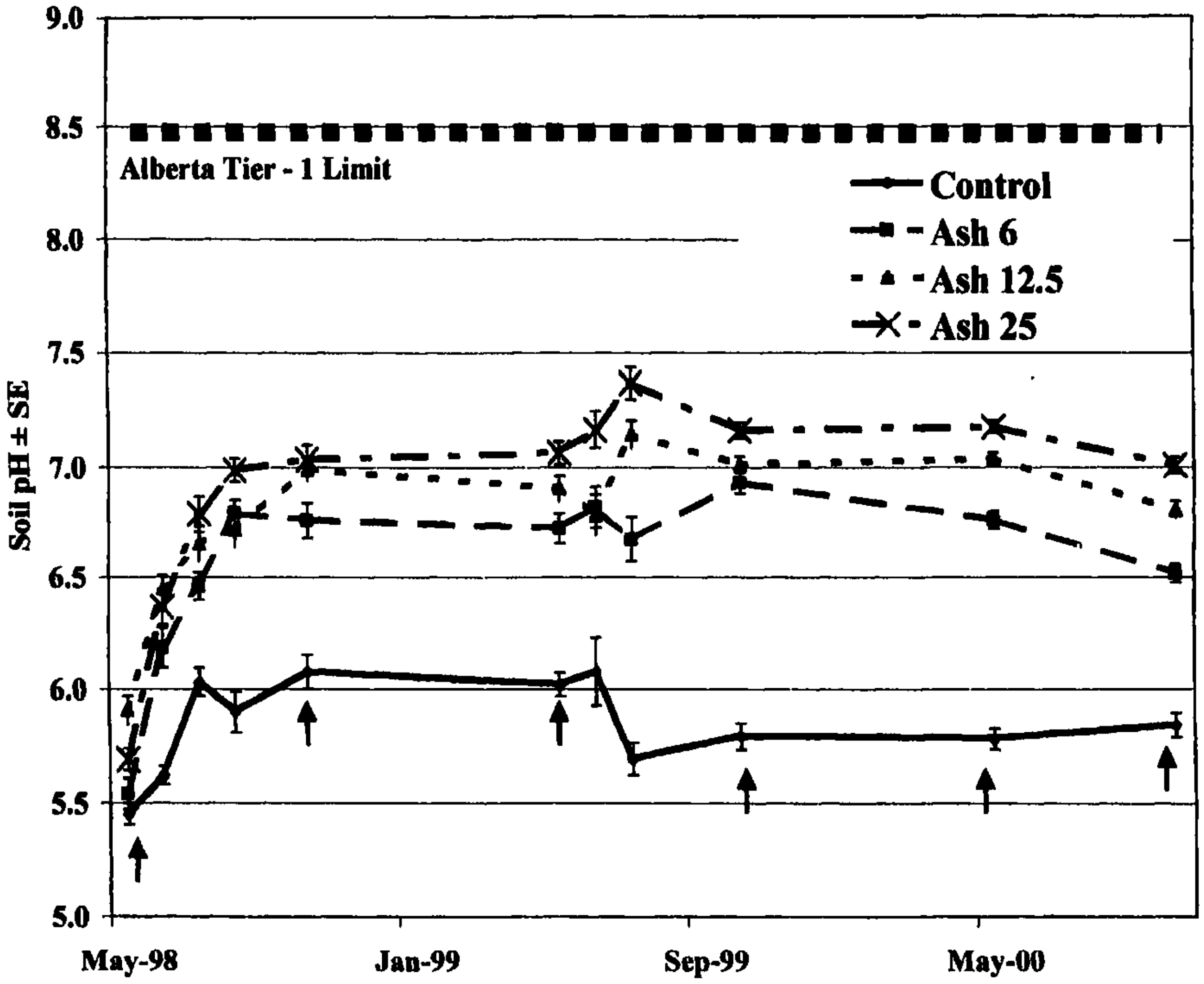

**Figure 1. Soil pH in 0.01M $CaCl_2$ (1:2) saturated pastes for soil samples taken from plots containing 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments during the study period (1998 - 2000); arrows indicate sampling sessions conducted in May and October.**

**Table 4. Soil pH in de-ionized water (1:2) saturated pastes for samples taken in May and October from plots containing applications of 6, 12.5 and 25 t ha$^{-1}$ wood ash and control treatments (1998 - 2000).**

| | *Soil pH: De - Ionized Water (pH ± SE)* | | | | | |
|---|---|---|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *1998* | | *1999* | | *2000* | |
| | *May* | *October* | *May* | *October* | *May* | *October* |
| *# Of Days From Wood Ash Incorporation* | *-17* | *+135* | *+348* | *+500* | *+714* | *+866* |
| *Control* | 6.1 ± 0.04C | 6.7 ± 0.07cB | 6.9 ± 0.07cA | 6.7 ± 0.06bB | 6.6 ± 0.04cB | 6.9 ± 0.04cA |
| *Ash 6* | 6.4 ± 0.06aD | 7.2 ± 0.07bBC | 7.3 ± 0.06bAB | 7.3 ± 0.06aB | 7.2 ± 0.04bBC | 7.1 ± 0.05bC |
| *Ash 12.5* | 6.6 ± 0.07aD | 7.3 ± 0.05abBC | 7.3 ± 0.07bC | 7.4 ± 0.04aBC | 7.4 ± 0.05aBC | 7.6 ± 0.05aA |
| *Ash 25* | 6.5 ± 0.07aD | 7.4 ± 0.05C | 7.6 ± 0.07aA | 7.4 ± 0.06aBC | 7.6 ± 0.05aAB | 7.7 ± 0.05aA |

* Means and Standard error (SE) followed by the same letter (A-D: within row; a-c: within column) are not significantly different at P=0.0001 level; means separated using Fisher's Protected LSD Test

-/+: (-) Indicates the number of days before wood ash was incorporated, (+) indicates the number of days after incorporation.

**Table 5. Soil EC in de-ionized water (1:2) saturated pastes for samples taken in May and October from plots containing applications of 6, 12.5 and 25 t ha$^{-1}$ wood ash and control treatments (1998 - 2000).**

| | *Electrical Conductivity (dS m$^{-1}$ ± SE)* | | | | | |
|---|---|---|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *1998* | | *1999* | | *2000* | |
| | *May* | *October* | *May* | *October* | *May* | *October* |
| *# of Days from Wood Ash Incorporation* | *-17* | *+135* | *+348* | *+500* | *+714* | *+866* |
| *Control* | 0.12 ± 0.01aA | 0.11 ± 0.00dA | 0.12 ± 0.01bA | 0.11 ± 0.01cA | 0.07 ± 0.00cB | 0.07 ± 0.00cB |
| *Ash 6* | 0.11 ± 0.01aBC | 0.19 ± 0.01cA | 0.12 ± 0.01bB | 0.18 ± 0.01bA | 0.09 ± 0.00bC | 0.09 ± 0.01bC |
| *Ash 12.5* | 0.10 ± 0.01aC | 0.22 ± 0.01bA | 0.14 ± 0.01bB | 0.16 ± 0.01cB | 0.09 ± 0.00bC | 0.09 ± 0.01bC |
| *Ash 25* | 0.12 ± 0.01aD | 0.28 ± 0.02aA | 0.18 ± 0.01aC | 0.23 ± 0.01aB | 0.13 ± 0.01aD | 0.13 ± 0.01aD |

* Means and Standard error (SE) followed by the same letter (A-D: within row; a-d: within column) are not significantly different at P=0.0001 level; means separated using Fisher's Protected LSD Test

-/+: (-) Indicates the number of days before wood ash was incorporated, (+) indicates the number of days after incorporation.

### *2.4.3. Soil Nutrients*

Treatment and sampling-sessions had a significant impact on soil nutrient levels. The two main effects had significant impact on available levels of P, S, $B_{HWS}$, and Fe levels within the soil (Table 6). Available Mn was only affected by the sampling-session. Treatment-by-sampling-session interactions were only significant for available levels of K and Zn (Table 6) in the soil.

The level of available P in 6 and 12.5 t ha$^{-1}$ treatments, in our study, was significantly lower than the 25 t ha$^{-1}$ treatment; no significant differences were observed among the ash treatments and the control plots. Available P decreased annually over the course of this study; levels in the third year were significantly lower than those in the first year (Appendix C - Table 45). Available S and B levels in 25 t ha$^{-1}$ plots were significantly higher than those in the control (Table 7). Levels fluctuated during the study and were highest in the first and second year after application (Appendix C - Table 45). Available Fe levels were significantly lower in all treatments containing ash additions, possibly due to the increase in soil pH as a result of ash applications (Table 7). Iron and Mn levels within the soil decreased after the first year of the study (Appendix C - Table 45).

Significant treatment-by-sampling-session interactions were found for available levels of K and Zn. Available K levels were higher in all treatments containing wood ash throughout the study; levels were significantly greater in 12.5 and 25 t ha$^{-1}$ applications. Increases in available Zn were observed in soils treated with 12.5 and 25 t ha$^{-1}$ ash. Available Zn was significantly greater in the first year after initial ash applications in the 25 t ha$^{-1}$ treatments. Available Zn was elevated in plots amended with wood ash but have decreased over time and by the third year was significantly different from the control (Table 45). Trends showed available levels of K and Zn increased with increasing application rates of wood ash.

**Table 6. Probability of F values for soil P, K, S, B, Cu, Fe, Mn, and Zn nutrient analysis for wood ash and control treatments (Treat), N – fertilizer (Fert), soil sampling-sessions conducted in May and October (session), crop, and their respective interactions for samples collected from plots containing N - fertilizer over the three-year period of the study (1998 – 2000).**

| *Source* | *df* | *P* | *K* | *S* | *B* | *Cu* | *Fe* | *Mn* | *Zn* |
|---|---|---|---|---|---|---|---|---|---|
| | | *Probability* | | | | | | | |
| *Total* | *143* | | | | | | | | |
| *Rep* | *3* | **** | * | n/s | *** | n/s | ** | * | **** |
| *Treat* | *4* | * | **** | * | **** | n/s | **** | n/s | **** |
| *Session* | *5* | **** | **** | * | **** | n/s | **** | **** | **** |
| *Crop* | *1* | n/s | n/s | * | ** | n/s | *** | *** | n/s |
| *Treat*Session* | *15* | n/s | **** | n/s | n/s | n/s | n/s | n/s | **** |
| *Treat*Crop* | *3* | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s |
| *Session*Crop* | *5* | n/s | n/s | n/s | n/s | n/s | **** | *** | n/s |
| *Treat*Session*Crop* | *15* | n/s | n/s | * | n/s | n/s | n/s | n/s | n/s |
| *Residual* | *94* | | | | | | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

**Table 7. Average nutrient concentrations of P, S, B, and Fe in soil samples taken from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| *Treatment (t ha$^{-1}$)* | *kg ha$^{-1}$ ± SE* | | | |
|---|---|---|---|---|
| | *P* | *S* | *B* | *Fe* |
| *Control* | 48.06 ± 4.80ab | 28.55 ± 9.70c | 1.69 ± 0.06b | 143.69 ± 8.09a |
| *Ash 6* | 40.12 ± 3.71b | 30.15 ± 2.41bc | 1.78 ± 0.07b | 95.81 ± 7.06b |
| *Ash 12.5* | 39.29 ± 3.05b | 46.99 ± 9.88ab | 1.80 ± 0.06b | 94.62 ± 6.11b |
| *Ash 25* | 54.95 ± 6.75a | 55.42 ± 7.41a | 2.08 ± 0.08a | 101.81 ± 6.51b |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (P & S) and P=0.0001 (B & Fe) levels; means separated using Fisher's Protected LSD Test

**Table 8. Concentration of available potassium in soil samples taken from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 - 2000).**

| Treatment (t ha$^{-1}$) | *Available Potassium (kg ha$^{-1}$ ± SE)* | | | | | |
|---|---|---|---|---|---|---|
| | *1998* | | *1999* | | *2000* | |
| | *May* | *October* | *May* | *October* | *May* | *October* |
| *# of Days* | *0* | *+152* | *+365* | *+517* | *+731* | *+883* |
| *Control* | 310.43 ± 40.98aA | 326.56 ± 15.14bA | 239.77 ± 13.13cAB | 168.75 ± 22.21bB | 175.84 ± 19.47cB | 210.19 ± 23.09bB |
| *Ash 6* | 271.23 ± 16.60aA | 251.63 ± 43.28bA | 287.65 ± 29.19cA | 274.40 ± 64.98aA | 212. 61 ± 40.22bcA | 212.80 ± 31.36bA |
| *Ash 12.5* | 243.32 ± 16.47aB | 318.64 ± 34.13bB | 493.55 ± 39.72bA | 243.23 ± 10.09aB | 281.49 ± 21.25bB | 275.33 ± 20.58abB |
| *Ash 25* | 326.69 ± 53.40aC | 692.40 ± 92.12aA | 628.13 ± 32.34aA | 287.09 ± 45.92aC | 423.92 ± 61.51aB | 349.63 ± 24.47aBC |

* Means and Standard error (SE) followed by the same letter (A-D: within row; a-c: within column) are not significantly different at P=0.0001 level; means separated using Fisher's Protected LSD Test

-/+: (-) Indicates the number of days before wood ash was incorporated, (+) indicates the number of days after incorporation.

**Table 9. Concentration of available zinc in soils samples taken from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| *Treatment (t ha$^{-1}$)* | *Available Zinc (kg ha$^{-1}$ ± SE)* | | | | | |
|---|---|---|---|---|---|---|
| | *1998* | | *1999* | | *2000* | |
| | *May* | *October* | *May* | *October* | *May* | *October* |
| *# of Days* | *0* | *+152* | *+365* | *+517* | *+731* | *+883* |
| *Control* | 13.34 ± 1.15aA | 9.79 ± 1.07bB | 9.16 ±1.31cB | 6.25 ± 0.61bC | 5.99 ± 0.72bC | 6.14 ± 1.73bC |
| *Ash 6* | 12.17 ± 1.44aA | 9.69 ± 1.24bAB | 10.42 ± 1.30cAB | 8.08 ± 0.92abC | 7.36 ± 0.94bC | 8.07 ± 1.05abBC |
| *Ash 12.5* | 12.50 ± 1.19aB | 9.26 ± 0.84bC | 15.73 ± 1.62bA | 9.74 ± 1.04aC | 8.62 ± 0.67abC | 9.31 ± 1.00aC |
| *Ash 25* | 13.29 ± 0.99aC | 18.22 ± 1.80aB | 21.19 ± 2.20aA | 9.69 ± 1.46aD | 10.13 ± 1.25aD | 10.36 ± 1.67aD |

* Means and Standard error (SE) followed by the same letter (A-D: within row; a-c: within column) are not significantly different at P=0.0001 level; means separated using Fisher's Protected LSD Test

-/+: (-) Indicates the number of days before wood ash was incorporated, (+) indicates the number of days after incorporation.

## 2.5. Discussion

The high pH, $CaCO_3$ equivalence, and nutrient content of the wood ash provide an opportunity for its use as a suitable nutrient supplement and liming agent for acidic soils. Wood ash application resulted in increased soil pH and nutrient status comparable to previous studies by Naylor and Schmidt (1989), Muse and Mitchell (1995), Krejsl and Scanlon (1996), and Meyers and Kopecky (1998) supporting Mitchell and Black (1997) who stated that provided wood ashes are used as soil liming amendments at recommended rates no environmental problems would be encountered. This would support the requirement for longer term studies to evaluate the availability of such elements added through wood ash applications as soil pH begins to decrease over time.

### *2.5.1. Soil Electrical Conductivity and pH*

No concerns resulted from the addition of wood ash at rates ranging from 6 to 25 t $ha^{-1}$ to the Luvisolic soils. Despite the considerably high pH (pH~13) and EC (50.3 dS m-1) of the wood ash, soils in this study amended with wood ash never exceeded Alberta Tier – 1 Guidelines for contaminated sites ($pHCaCl_2$=8.5; EC=2.0 dS $m^{-1}$) at any point during the three years. Soil pH in ash amended soils has remained significantly higher than the control, and has remained elevated after three years, similar to other findings by Naylor and Schmidt (1989), Muse and Mitchell (1995), and Meyers and Kopecky (1998). Alberta Agriculture (1996) states that the particle size of the material influences the reactivity and efficiency of the liming material. Naylor and Schmidt (1986) indicated the fineness of wood ash would allow quicker reaction with soil acidity. The particle size of the ash may play a role in the longevity of the pH increases in the field, however there were not any studies in the literature that could support this statement. Other non – replicated wood ash studies at Al – Pac continue to find elevated soil pH levels as a result of the initial applications conducted in 1996 and 1997. Only a slight difference in soil pH levels was evident in our study between 12.5 and 25 t $ha^{-1}$ applications suggesting that the soil's buffering capacity may result in limited changes in soil pH at higher application rates (Tisdale and Nelson, 1975). However, this is only speculative, as our results could not support this. This would suggest for example, if an application of 12.5 t ha$^{-1}$ wood ash was required, an over application up to 25 t ha$^{-1}$ would not result in a deleterious effect on soil pH.

### *2.5.2. Soil Cadmium and Zinc*

Applications of wood ash did not significantly increase Cd and Zn levels in the soil, which did not exceed upper limits set under Alberta Tier – 1 Guidelines for Contaminated Sites during the study. Zhan et al. (1996) evaluated the availability of trace elements in wood ash as pH was decreased. These authors found the solubility of heavy metals and trace elements, such as Cd and Zn, increased as pH was decreased below 6.5. The authors also indicated a substantial increase in Cd and Zn solubility as the pH was lowered to values below 5.5 to 6.0.

### *2.5.3. Soil Nutrients*

Very little of the applied P in the ash is in the available form (Appendix D). Naylor and Schmidt (1989) found that ash applications had little or no effect on available P, similar to what was found in this study. This effect may be due to the rate at which the P contained within the ash is made available for plant uptake, and suggests available P is gradually released over time with the plants taking up P as it becomes available. Ohno and Erich (1990) stated the amount of P released during the incubation of wood ash within the soil profile was not related to soil pH, but that reactions of P determine the availability of P. The addition of ash to the Luvisolic soil in this study resulted in elevated levels of S, K, B, and Zn, similar to results obtained by Naylor and Schmidt (1989) and Krejsl and Scanlon (1996). Available $B_{HWS}$ did not exceed the Alberta Tier – 1 Guideline limit of 2.0 mg kg$^{-1}$ or 5.2 kg ha$^{-1}$ (assuming 2, 600 t of soil in the top 0.2-m and a soil bulk density of 1.3 t m$^{-1}$ for clay loam (Wolf, 1990)). Boron levels in our study decreased in the soil to levels comparable to $B_{HWS}$ concentrations found within the control.

Erich (1991) stated additions of wood ash can result in increased P and K. At high application rates, exceeding 50 t $ha^{-1}$, pH, B, and K may limit plant growth if B and K exceed phytotoxic levels (Etiegni et al., 1991a). This was not the case for our study. Naylor and Schmidt (1989) found wood ash applications resulted in elevated levels of exchangeable Ca, Mg, and K and decreased levels of exchangeable Fe and Al. Our study found significant decreases in available Fe and Mn within the soil. However, only available Fe levels in the soil were significantly lower within ash treatments compared to the control, probably related to the increase in soil pH observed in these same plots. No significant difference for available Mn was observed among treatments. Krejsl and Scanlon (1996) found reduced levels of Cu, Fe, Mn, and Zn but also observed increased levels of S and B as a result of ash applications. This suggests that wood ash can provide a suitable source of K, S, B, and Zn as well as possible gradual amounts of P over time.

### *2.5.4. Future Studies: Wood Ash and Soil Properties*

The effects that multiple ash applications have on soil physical and chemical properties still needs to be addressed. Various studies have evaluated single applications at high rates. Although these are useful in determining rates at which toxic symptoms may appear, their practical use in agriculture is unlikely. Realistically, multiple applications at lower rates will be more common. Little information in the literature was available at the time of this study of the effect multiple applications at a single location would have on the chemical and physical properties of receiving soils.

## 2.6. Conclusion

Wood ash applications <25 t $ha^{-1}$ increased soil pH and available levels of B, K, S, and Zn while, decreasing available levels of Fe in the Luvisolic soil chosen for the study. Minimal differences were observed in both soil pH and available nutrient level between the 12.5 and 25 t

$ha^{-1}$ application rates used in this study. This suggests minimal benefits would be observed in the short term (i.e. 3 years) when applying ash at rates greater than 12.5 t $ha^{-1}$. Soil nutrient and pH levels continued to remain elevated three years after initial application while, remaining below upper limits set by Alberta Tier – 1 Guidelines.

Wood ash is an economically valuable resource, which can be used as an alternative to agricultural lime, and as a supplemental nutrient source for crop production. Agronomic applications (<50 t $ha^{-1}$) of wood ash can have positive effects on soil properties. Under reliable management programs, wood ash application can be done sustainably to benefit agricultural production without exceeding any environmental regulations, while reducing the costs of their disposal.

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# *CHAPTER THREE: CROP PRODUCTION*

## 3. EFFECT OF WOOD ASH APPLICATIONS ON THE PRODUCIVITY OF BARLEY (*HORDEUM VULGARE* L.) AND ON CANOLA (*BRASSICA RAPA* L.) NEAR BOYLE, ALBERTA

### 3.1. Introduction

Agricultural production in Western Canada is limited by many factors including nutrient deficiencies and soil acidity. These factors reduce the production capability in many areas in Canada; to overcome these problems producers use various fertilizers and agricultural lime products. Synthetic fertilizers and agricultural wastes are widely used in agricultural production. While liming is common practice in many regions, prohibitive factors such as transportation have limited the use of lime in Western Canada.

Wood ash is produced by energy producing systems, or cogeneration plants, from the incineration of hog fuel (waste wood, bark, etc.) to produce heat, steam and electricity. Wood ash is being evaluated in land application programs as a waste disposal alternative. Until recently landfilling has been the primary practice for disposing wood ash generated in this process. United States generates upwards of 2.7 million tonnes of ash on an annual basis; nearly 90% of the generated wood ash is landfilled with 10% being applied to land (Campbell, 1990). Hence, wood ash is becoming a significant disposal problem. Stricter environmental regulations and prohibitive costs associated with landfilling have led to alternative, less costly sustainable methods of disposal, like land application being sought (Campbell, 1990). Wood ash has many properties that would benefit agricultural crop production, including its use as an alternative liming agent. Wood ash has high pH (~13), and nutrients that can supplement essential micro and macronutrients to plants. Utilization of wood ash in land application programs as an alternative soil amendment has the potential to provide a waste disposal substitute significantly reducing the volume of ash deposited annually within landfill sites. It is estimated that in Alberta approximately 110, 000 t of wood ash are generated annually from these cogeneration systems. The Kraft pulp mill operated by Alberta – Pacific Forest Industries near Boyle, AB, generates about 16, 000 t of wood ash annually, and is interested in finding an alternative use for this product. Farmers for centuries have recycled ashes back into the system during clearing of forests to increase arable lands (Hopkins 1910; Giovannini et al., 1993). As a result, yields in these areas were often increased through the change in soil chemistry, and release of essential elements required for growth.

Agronomic benefits resulting from the land application of pulp and paper mill by-products have been widely studied in Europe (Karsisto, 1979), United States (Vance, 1996; Mitchell and Black, 1997), and more recently Canada (Abboud and Buck, 1998; Lickacz et al., 1998; Bertschi, 2000), as soil amendments for crop production. Applications of wood ash have increased dry matter and nutrient quality in many crops (Table 1). Applications of ash at rates less than 50 t ha$^{-1}$ in greenhouse studies have increased dry matter in oats (*Avena sativa* L.) as much as 45% (Krejsl and Scanlon, 1996); in wheat (*Triticum aestivum* L.) up to 69% (Eteigni et al., 1991b); 64% in beans (*Phaseolus vulgaris* L.) (Krejsl and Scanlon, 1996); 400% in barley and 260% in alfalfa (Meyers and Kopecky, 1998). In field studies, rates less than 50 t ha$^{-1}$ have resulted in biomass increases up to 15% in wheat (*Triticum aestivum* L.) (Huang et al., 1993); in alfalfa (*Medicago sativa* L.) by nearly 58% (Meyers and Kopecky, 1998); and forages from 36% to 144% (Naylor and Schmidt, 1989; Muse and Mitchell, 1995; Meyers and Kopecky, 1998). Although our study did not evaluate rates greater than 25 t ha$^{-1}$ differing views exist about advantages of applying ash at application rates exceeding 40 t ha$^{-1}$. For example in the greenhouse, Meyers and Kopecky (1998) showed significant increases in dry matter yield in alfalfa and barley at ash application rates from 50 to 90 t ha$^{-1}$. While Krejsl and Scanlon (1996) found significant increases in the biomass of oats at rates of 30 and 40 t ha$^{-1}$ with the lowest biomass occurring at 50 t ha$^{-1}$. Etiegni et al. (1991a) found applications in excess of 40 t ha$^{-1}$ had detrimental effects on wheat biomass, growth of poplar (i.e. calliper and height) within ash amended plots at application rates of 320 and 640 t ha$^{-1}$. Studies continue to show wood ash, as an agricultural amendment, is capable of improving productivity of many crops. Increases in dry matter production, as a result of ash applications, are evident in many studies.

## 3.2. Objective

The focus of this study was to determine the effect wood ash applications have on the growth of barley and canola grown in Central Alberta on soils in the Luvisolic Region. The effect of wood ash application on crop production was studied under field conditions, using conventional farm equipment to apply wood ash. Liming value of the ash was not separated from the nutrient value of the wood ash. Two criteria were used to determine the application rates used in this study. The first was rate selection based on results obtained from an earlier greenhouse study (Bertschi, 2000) and other literature sources. The second consideration was for rates that could be economically and logistically feasible for agricultural production. Objectives for the field study were:

1. To assess the effects of wood ash applications under field conditions on barley and canola production.
2. To determine the duration of time such applications can be effective.
3. To determine whether nitrogen fertilizer application will have a synergistic effect and increase the benefits from wood ash applications.

## 3.3. Methods and Materials

### *3.3.1. Study Design*

The site chosen for the study had been continuously cropped to hay before the study began, and is located in the Luvisolic soil zone (Appendix A - Figure 6). The quarter section (SE1/4 22-68-19W4) was divided into three blocks, located in the NE, NW, and SE portion of the section (Appendix A - Figure 7). A randomized complete block design was used for the experiment with three replications; with each of the treatments consisting of the following four ash loading rates: 0, 6, 12.5 and 25 t $ha^{-1}$. Trials located in the NW and SE area of the quarter were 50-m wide by 300-m long; the trial in the NE portion was 30-m wide and 250-m long. A 3-m buffer zone was used to separate the three crops and wood ash treatments used in the study. The buffer was rotovated twice each year to a depth of 0.2-m. Each of the wood ash plots was further divided into three sections for seeding a canola and two barley cultivars. Crops were seeded perpendicular to wood ash and nitrogen applications.

### *3.3.2. Ash*

The mill supplying the wood ash for our study operates a power boiler fueled by wood waste and natural gas producing about 16, 000 tonnes of wood ash annually through the incineration of wood waste (knots, chips, bark, etc.) as fuel for the generation of heat for pulp production. The wood ash is produced from hardwood and softwood waste wood and bark used as fuel, and has been characterized extensively for physical characteristics, available nutrients, total nutrients, available metals, and total metals (Appendix D). Wood ash was stockpiled on-site in SE1/4 22-68-19W4 prior to application from March 1998 to mid-May 1998. Ash was applied in the last week of May in 1998 using a side discharge GEHL Scavenger Manure Spreader (Appendix E), calibrated to apply wood ash at 6, 12.5 and 25 t $ha^{-1}$. After application the ash was incorporated, by disc, to a depth of 0.2-m and allowed to incubate 5 days before seeding occurred.

### *3.3.3. Soils*

The site of the field trial was located at SE1/4 22-68-19W4, approximately 25 km NW of Boyle, AB, in Orthic Gray Luvisol soils (Appendix A - Figure 6). The site is complex in nature with a classification of 80% Tolman, 10% Tawatinaw, and 10% Amisk soils with a gently undulating slope of 2% to 4% (Report No. 29, 1972). Amisk soil groups are part of the

Degraded Brunisols while, both the Tolman and Tawatinaw groups belong to the Orthic Gray Luvisols. The soil horizons are Ae, Bt, and Ck and are moderate with a pH of 5.5 to 6 and silt loam texture (Report No. 29, 1972). The main soil group consist of Tolman soils that have developed on well-drained parent material under forest vegetation, which primarily consists of hardwood species such as aspen, poplar, and white birch (Report No. 29, 1972).

### *3.3.4. Crops*

Barley and canola are valuable crops in Alberta, and are commonly grown crops in the Prairie Provinces of Canada (Agrium, 1997). Barley (*H. vulgare* L.) cultivars used in this study included six-row cv. 'AC Lacombe' barley commonly used for silage and feed grain (Kibite, 1993) and two – row cv. 'Harrington' barley used in malting (Harvey and Rossnagel, 1984) (Appendix F: Figure 12 to Figure 13). A Polish canola (*Brassica rapa* L.) cultivar 'Maverick'; was also chosen for the study because of its early maturity (Appendix F: Figure 14). All crops were fertilized and seeded in the last week of May during the three years of the study. Trials were seeded with two barley cultivars at a rate of 112 kg ha$^{-1}$ using a John Deere Air Seeder, and the Polish canola cultivar, 'Maverick', at a rate of 7.8 kg ha$^{-1}$ using a Valmar Airflo Seeder. Crops were seeded in the same locations for all three years of the study. Half of each plot was fertilized by banding with urea (46-0-0) to provide 130 kg ha$^{-1}$ (56 kg ha$^{-1}$ 1998; 103 kg ha$^{-1}$ 1999; 108 kg ha$^{-1}$ 2000) of nitrogen based on soil fertility analysis. Weed control, in 1998, in the canola was conducted using the pre-emergent herbicide Edge™ and by spraying using Lontrel 360™ with Poast Ultra™ and Merge™ in early July. Weed control within the barley was done using Refine Extra™ and Assert™. A pre-harvest application of Round-up™ was applied in early-September of 1998 for dessication of barley and canola. Similar weed control measures were conducted in 1999 and 2000; only the pre-harvest dessication in early-September was not performed in the last two years.

To determine dry matter production samples from both cultivars were collected during the 'soft dough' stage (before ripening occurred) after 70 days in 1998, 72 days in 1999, and 72 days in 2000 after seeding. Dry matter yield on 'AC Lacombe' barley was determined in all three years of the study, while, dry matter yield on 'Harrington' barley was determined during the last two years. Grain yield was determined in all three crops at maturity 107 days (1998), 103 days (1999), and 105 days (2000) after seeding occurred.

Dry matter yield was estimated on whole plant samples clipped 5-cm above the ground from an area of 0.25-m$^2$ for 'AC Lacombe' (n=30) and 'Harrington' (n=6) barley cultivars from each of the three replications. Weeds were separated at the site and removed from all of the samples collected for dry matter. Weed control was good in 1998 and 1999, however wild oats and buckwheat were present in 2000 within the field trials. Weed populations were approximately 2% of 'AC Lacombe' plots, and 5% of 'Harrington' barley plots and were relatively similar in all replications. Similar observations were made for 'Maverick' canola that contained buckwheat. Samples were collected and dried at 55°C for six days; only the nitrogen control plots were sampled in 1998. After drying samples were weighed to determine dry matter weight, and sent for plant tissue analysis to EnviroTest Laboratories (Calgary, AB).

An independent research company, Gateway Research Organization (GRO) from Westlock AB, conducted grain yield sampling using a Wintersteiger Nurserymaster Elite combine to harvest grain and oilseed plots. Randomly selected samples (n=12) were taken for each of the barley and canola plots from both N – fertilized and unfertilized areas of the treated plots. Seed samples were harvested from standard 9-m$^2$ areas (1.5-m wide by 6-m long). Only the nitrogen plot was sampled from the control in 1998; samples were collected and dried at 55°C for three days. Sub-samples of the barley and canola were then sent to EnviroTest Laboratories (Calgary, AB) for chemical analysis; and the remaining sample sent to GRO to be cleaned and yield determined. Samples were cleaned using an Almaco Seed Cleaner (Allan Machine Company, Nevada, IA), and weighed to determine yield.

## 3.4. Climatic Data

Climatic factors, such as temperature and rainfall, play a significant role in the development and productivity of all agricultural crops. The Athabasca region typically receives approximately 500-mm of total precipitation (Appendix B: Table 42 & Figure 8) annually based on a 40-year average from 1959 to 1999 (Environment Canada data). Precipitation data obtained from Environment Canada showed during the three years (1998 to 2000) the level of precipitation within the area was less than the 40-year average. The total precipitation received was 32, 15, and 24% lower than the long - term average in 1998, 1999, and 2000, respectively. The average temperature from May to August during the course of the study was very similar to the 40-year average for the area (Appendix B: Table 43 & Figure 9).

### *3.4.1. Statistical Analysis*

Tests to satisfy assumptions set by the ANOVA test were conducted and were supported. Analysis of variance was conducted on data collected for dry matter and grain yield using the statistical program AGROBASE$^{TM}$ 99 (Agronomix, 1999). Fisher's Protected Least Significant Difference (LSD) test, at the P=0.05, P=0.01, P=0.001, and P=0.0001 levels were used to separate means once statistical differences were observed.

## 3.5. Results

### *3.5.1. Barley Dry Matter Production*

Ash applications had a positive impact on the dry matter production of the two barley cultivars 'AC Lacombe' and 'Harrington'. The main effects treatment, year, fertilizer, and treatment-by-fertilizer interaction, were significant for 'AC Lacombe' and 'Harrington' barley (Table 10).

**Table 10. Probability of F values for barley dry matter yield for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their respective interactions for samples collected from plots with and without N – fertilizer (1999 - 2000).**

| | *Dry Matter Yield (t ha$^{-1}$)* | | | |
|---|---|---|---|---|
| | *'AC Lacombe'* | | *'Harrington'* | |
| *Source* | *df* | *Probability* | *df* | *Probability* |
| *Total* | *479* | | *95* | |
| *Rep* | *2* | n/s | *2* | n/s |
| *Treat* | *3* | **** | *3* | **** |
| *Year* | *1* | **** | *1* | **** |
| *Fert* | *1* | **** | *1* | **** |
| *Treat*Year* | *3* | n/s | *3* | n/s |
| *Treat*Fert* | *3* | **** | *3* | * |
| *Year*Fert* | *1* | **** | *1* | ** |
| *Treat*Fert*Year* | *3* | n/s | *3* | n/s |
| *Residual* | *462* | | *78* | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

Significant increases in dry matter production were observed for 'AC Lacombe' in all nitrogen – ash amended plots (Figure 2) compared to the control. In wood ash treatments, average increases in 'AC Lacombe' dry matter ranged from 13 to 31% in unfertilized plots versus increases of 27 to 50% in plots with N – fertilizer during 1999 and 2000 (Figure 2). The 12.5 and 25 t ha$^{-1}$ ash amended plots (unfertilized) showed no significant differences from the fertilized control. Dry matter production was significantly greater in 1999 (8.92 ± 0.15 t ha$^{-1}$) than 2000 (7.62 ± 0.18 t ha$^{-1}$), while plots containing N – fertilizer (9.83 ± 0.14 t ha$^{-1}$) exhibited significantly greater yields than unfertilized plots (6.71 ± 0.14 t ha$^{-1}$).

'Harrington' barley dry matter from nitrogen – ash amended plots showed significant increases compared to the N – control (Table 11). Increases in 'Harrington' dry matter in ash treatments on average ranged from 25% to 27% in unfertilized plots while, increases were in the order of 57 to 65% in plots treated with N – fertilizer during 1999 and 2000 (Table 11). Yields

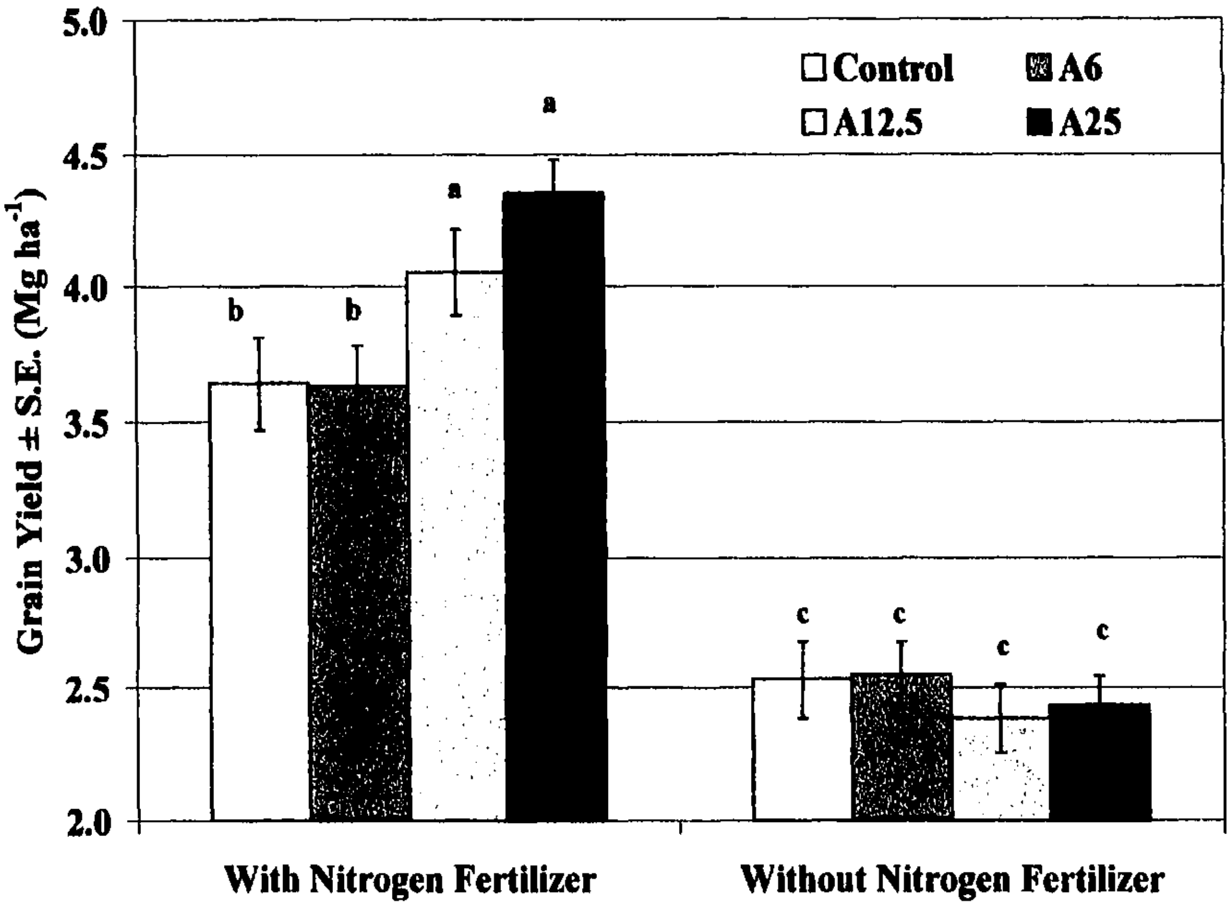

**Figure 2.** *H. vulgare* L. cv. 'AC Lacombe' dry matter yield, results shown are averages of whole plant samples taken from 0.25-m$^2$ areas in each treatment with and without nitrogen fertilizer from 6 (A6), 12.5 (A12.5), and 25 (A25) t ha$^{-1}$ wood ash and control treatments (1999 – 2000). Columns with the same letter are not significantly different at the P=0.0001 level; means separated using Fisher's Protected LSD Test.

from plots containing N – fertilizer (9.55 ± 0.35 t ha$^{-1}$) were significantly greater than those for unfertilized plots (6.46 ± 0.30 t ha$^{-1}$). Dry matter production in 1999 (8.95 ± 0.34 t ha$^{-1}$) was significantly greater than in 2000 (7.05 ± 0.40 t ha$^{-1}$).

**Table 11. *H. vulgare* L. cv. 'Harrington' barley dry matter yield, data shown are the average yields of whole plant samples taken from each of the wood ash treatments in plots with and without N – fertilizer (1999 - 2000).**

| | *Dry Matter Yield (t ha$^{-1}$ ± SE)* | |
|---|---|---|
| *Treatment (t ha$^{-1}$)* | *Without N – Fertilizer* | *With N – Fertilizer* |
| *Control* | 5.25 ± 0.67b | 6.51 ± 0.36b |
| *Ash 6* | 6.66 ± 0.47b | 10.20 ± 0.48a |
| *Ash 12.5* | 7.13 ± 0.65b | 10.74 ± 0.59a |
| *Ash 25* | 6.79 ± 0.46b | 10.75 ± 0.50a |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.01 level; means separated using Fisher's Protected LSD Test.

Treatment, year, and the treatment-by-year interactions (Table 12) were significant for 'AC Lacombe' in plots with N – fertilizer. Only the treatment effect was significant for 'Harrington' barley (Table 12).

**Table 12. Probability of F values for barley dry matter yield for treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with N – fertilizer.**

| | *Dry Matter Yield (t ha$^{-1}$)* | | | |
|---|---|---|---|---|
| | *'AC Lacombe' (1998-2000)* | | *'Harrington' (1999-2000)* | |
| *Source* | *df* | *Probability* | *df* | *Probability* |
| *Total* | *359* | | *47* | |
| *Rep* | *2* | n/s | *2* | n/s |
| *Treat* | *3* | **** | *3* | **** |
| *Year* | *2* | **** | *1* | n/s |
| *Treat*Year* | *6* | * | *3* | n/s |
| *Residual* | *346* | | *38* | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

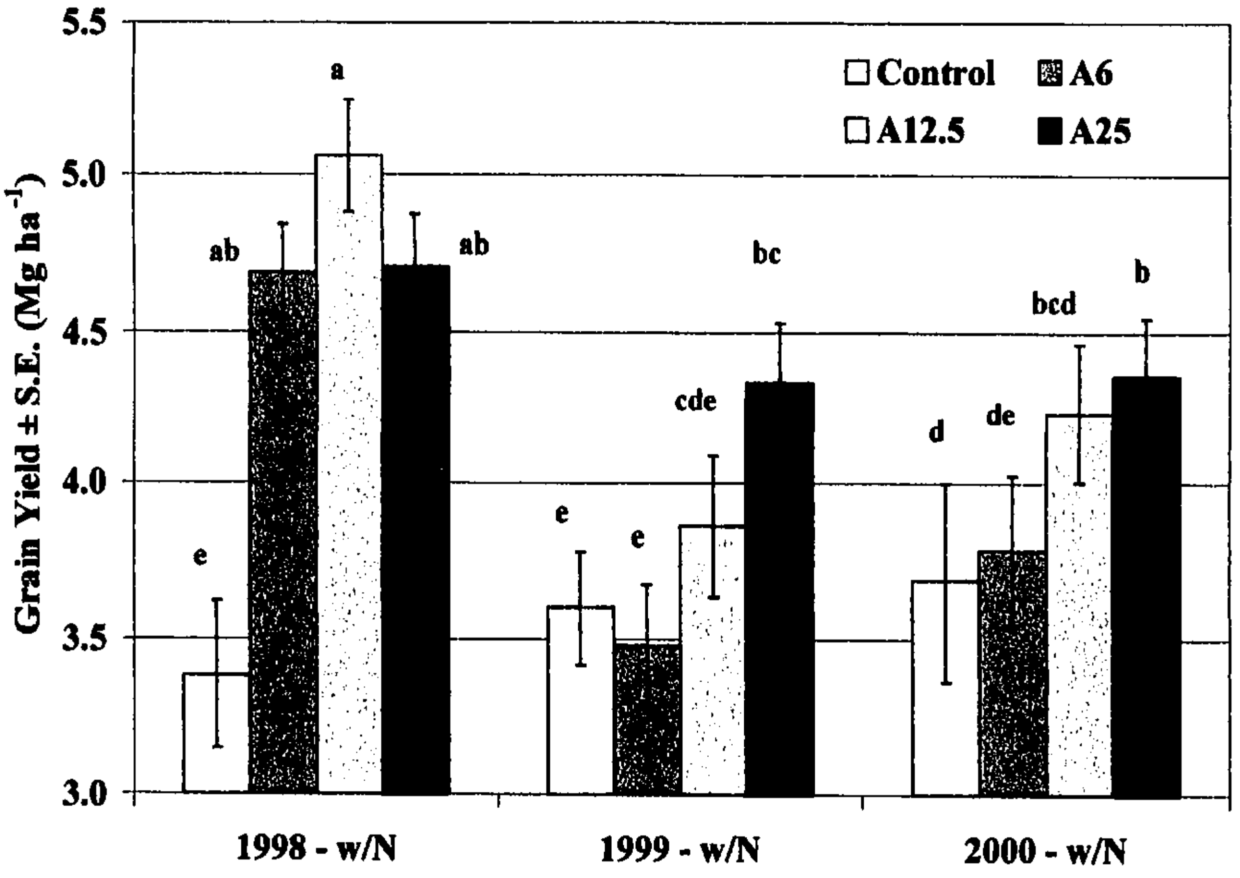

Figure 3. *H. vulgare* L. cv. 'AC Lacombe' dry matter yield, results shown are averages of whole plant samples taken from a 0.25-m$^2$ area in plots containing 6 (A6), 12.5 (A12.5), and 25 (A25) t ha$^{-1}$ wood ash and control treatments with N - fertilizer (1998 – 2000). Columns with the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test.

Data collected for all three years, from trials containing N – fertilizer showed a significant increase in the dry matter for 'AC Lacombe' (Figure 3). Average 'AC Lacombe' dry matter production in 1998 (8.13 t ha$^{-1}$) was significantly less than in 1999 (9.98 t ha$^{-1}$) and in 2000 (9.68 t ha$^{-1}$). Increases in 'AC Lacombe' dry matter from ash treatments ranged from 23 to 72%, 28 to 57%, and 26 to 42% in 1998, 1999, and 2000, respectively in plots with N – fertilizer. Results show that wood ash applications of 25 t ha$^{-1}$ consistently had the greatest effect on dry matter production in all three years.

Averages for 'Harrington' barley dry matter production (Table 11) were increased 57% to 61% as a result of ash treatments in plots with N – fertilizer during 1999 and 2000. Significant differences were mainly between the control and ash treatments, and not among the ash treatments themselves.

In plots without nitrogen fertilizer, in the last two years of the study, treatment and year effects on barley dry matter production, of both cultivars, were significant (Table 13). No significant treatment-by-year interaction was evident for either barley cultivar.

**Table 13. Probability of F values for barley dry matter yield for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots without N – fertilizer (1999 – 2000).**

| | | *Barley Dry Matter Yield (t ha$^{-1}$)* | | |
|---|---|---|---|---|
| | | *'AC Lacombe'* | | *'Harrington'* |
| *Source* | *df* | *Probability* | *df* | *Probability* |
| *Total* | *239* | | *47* | |
| *Rep* | *2* | n/s | *2* | n/s |
| *Treat* | *3* | **** | *3* | ** |
| *Year* | *1* | **** | *1* | **** |
| *Treat*Year* | *3* | n/s | *3* | n/s |
| *Residual* | *230* | | *38* | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

Ash treatments had a significant effect on 'AC Lacombe' dry matter in unfertilized plots in 1999 and 2000 (Table 14). Average increases of 13 to 31% were observed as result of ash treatments in unfertilized plots (Table 14). Dry matter resulting from 12.5 and 25 t ha$^{-1}$ ash treatments was significantly higher than that for the control and 6 t ha$^{-1}$ ash treatments. Average dry matter production in 1999 (7.87 ± 0.15 t ha$^{-1}$) was significantly greater than in 2000 (5.56 ± 0.15 t ha$^{-1}$) for 'AC Lacombe' barley.

**Table 14. Dry matter yield results for *H. vulgare* L. cv. 'AC Lacombe' data shown are averages of 0.25-m$^2$ whole plant samples taken from 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments in plots without N – fertilizer (1999 – 2000).**

| *Treatment (t ha$^{-1}$)* | *Dry Matter Yield (t ha$^{-1}$ ± SE)* |
|---|---|
| *Control* | 5.74 ± 0.24c |
| *Ash 6* | 6.46 ± 0.24b |
| *Ash 12.5* | 7.12 ± 0.27a |
| *Ash 25* | 7.53 ± 0.23a |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.0001 level; means separated using Fisher's Protected LSD Test

Treatment and year effects had significant impacts on 'Harrington' barley dry matter production (Table 13). Significant increases in dry matter were observed in wood ash treatments (Table 11) when compared with the controls; no significant differences were observed among the different ash treatments. Average increases of 27 to 36% were observed in 'Harrington' dry matter production in unfertilized ash treatments in 1999 and 2000 (Table 11). Average dry matter production was significantly greater in 1999 (7.90 ± 0.32 t ha$^{-1}$) than in 2000 (5.01 ± 0.27 t ha$^{-1}$).

### *3.5.2. Seed Yield of Barley and Canola*

In 1999 and 2000, the main effects of treatment, fertilizer, and year significantly affected 'Harrington' grain and 'Maverick' oilseed yield (Table 15). 'AC Lacombe' grain yield was significantly affected by the addition of N – fertilizer (Table 15). Treatment-by-fertilizer, showing the interaction of treatment and N – fertilizer, was found to be significant for all three crops in these treatments (Table 15).

'AC Lacombe' grain yields in plots with N – fertilizer were significantly greater than in unfertilized plots; 12.5 and 25 t ha$^{-1}$ treatments produced the largest yield increases (Figure

4). Ash applications increased 'AC Lacombe' grain yield up to 20% in plots with N – fertilizer while, no significant changes were observed in unfertilized plots in 1999 and 2000 (Figure 4).

**Table 15. Probability of F values for grain and oilseed yield for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with and without N – fertilizer (1998 – 2000).**

| | | Grain and Oilseed Yield (t $ha^{-1}$) | | |
|---|---|---|---|---|
| | | *'AC Lacombe' Barley* | *'Harrington' Barley* | *'Maverick' Canola* |
| *Source* | *df* | | *Probability* | |
| *Total* | *191* | | | |
| *Rep* | *2* | n/s | * | n/s |
| *Treat* | *3* | n/s | **** | **** |
| *Year* | *1* | n/s | **** | **** |
| *Fert* | *1* | **** | **** | **** |
| *Treat*Year* | *3* | n/s | n/s | n/s |
| *Treat*Fert* | *3* | ** | ** | **** |
| *Year*Fert* | *1* | ** | n/s | *** |
| *Treat*Fert*Year* | *3* | n/s | n/s | * |
| *Residual* | *174* | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

'Harrington' grain yield (Table 16) was significantly greater in plots containing N - fertilizer, similar to the 'AC Lacombe' results. Nitrogen – ash amended plots were significantly greater than the N – control or plots containing only wood ash. Average 'Harrington' grain yield was significantly greater in 1999 (2.98 ± 0.08 t $ha^{-1}$) than in 2000 (2.00 ± 0.06 t $ha^{-1}$). Average increases in unfertilized plots ranged from 5 to 14% and 22 to 36% in plots with N – fertilizer as a result of ash treatments from 1999 to 2000 (Table 16).

**Table 16. *H. vulgare* L. cv. 'Harrington' data shown are average yield from a 9-$m^2$ area harvested from 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments in plots with and without N – fertilizer (1999 – 2000).**

| | *Grain Yield (t $ha^{-1}$ ± SE)* | |
|---|---|---|
| *Treatment (t $ha^{-1}$)* | *Without N – Fertilizer* | *With N – Fertilizer* |
| *Control* | 1.92 ± 0.10e | 2.42 ± 0.13c |
| *Ash 6* | 2.17 ± 0.12d | 2.96 ± 0.15b |
| *Ash 12.5* | 2.18 ± 0.13d | 3.31 ± 0.19a |
| *Ash 25* | 2.01 ± 0.13de | 2.98 ± 0.14b |

a-e Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.01 level; means separated using Fisher's Protected LSD Test

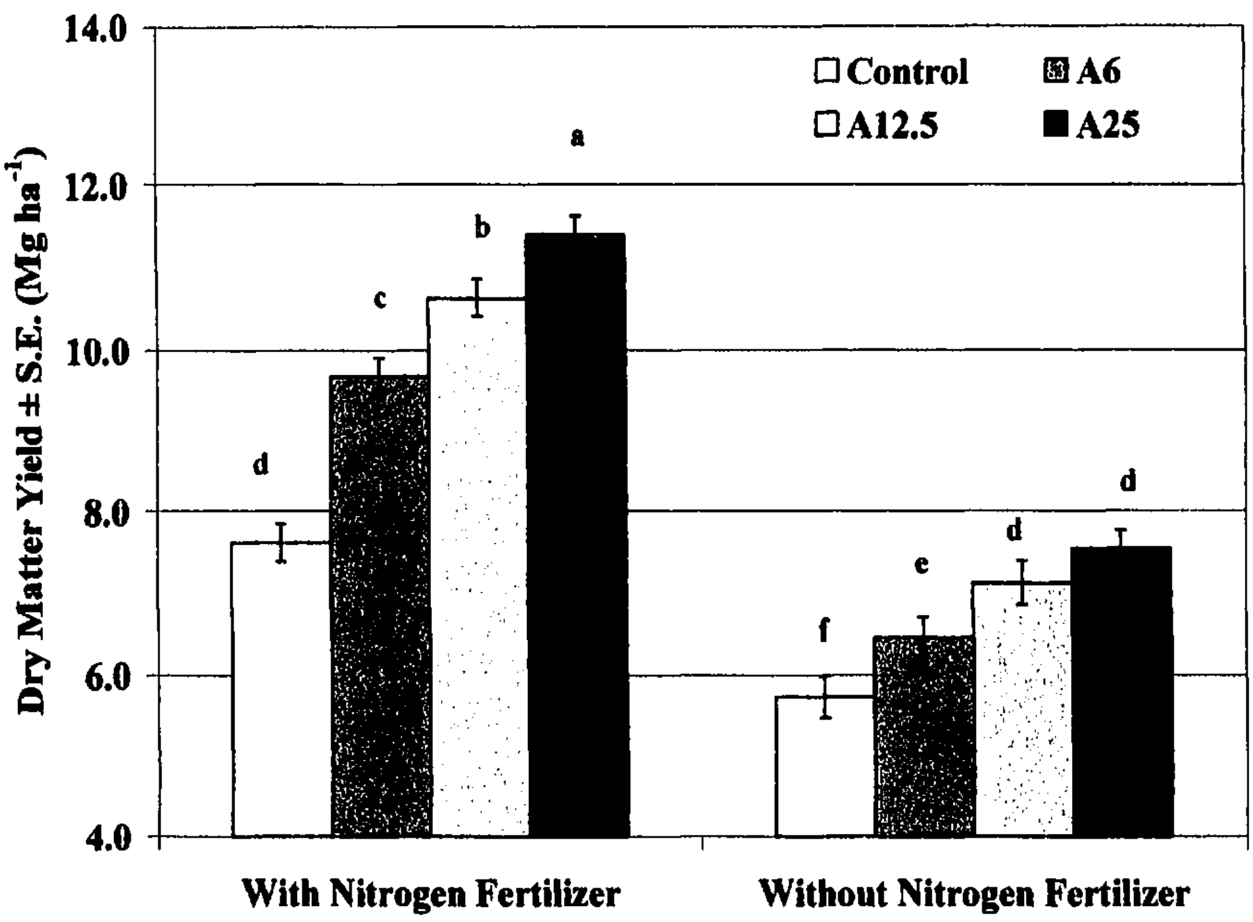

**Figure 4.** *H. vulgare* L. cv. 'AC Lacombe' grain yield, results shown are the averages of 9-m$^2$ areas harvested to determine yield from plots containing 6 (A6), 12.5 (A12.5), and 25 (A25) t ha$^{-1}$ wood ash and control treatments with and without nitrogen fertilizer (1999 – 2000). Columns with the same letter are not significantly different at the P=0.01 level; means separated using Fisher's Protected LSD Test.

Nitrogen fertilizer had a significant effect on the yield of 'Maverick' canola oilseed yield (Table 17). Nitrogen – ash amended plots had significantly greater yields than unfertilized plots; yields on ash amended plots were also significantly greater than those from the control. Average increases of 68 to 98% were observed in plots with N – fertilizer while increases ranged from 2 to 8% in unfertilized plots from 1999 to 2000 as a result of wood ash treatments (Table 17). 'Maverick' canola average yields were significantly greater in 1999 (0.95 ± 0.04 t $ha^{-1}$) than in 2000 (0.50 ± 0.02 t $ha^{-1}$).

**Table 17. *B. rapa* L. cv. 'Maverick' data shown are average yield from a 9-$m^2$ area harvested from 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments in plots with and without N – fertilizer (1999 – 2000).**

| | *Oilseed Yield (t $ha^{-1}$ ± SE)* | |
|---|---|---|
| *Treatment (t $ha^{-1}$)* | *Without N – Fertilizer* | *With N – Fertilizer* |
| *Control* | 0.63 ± 0.05c | 0.47 ± 0.05d |
| *Ash 6* | 0.64 ± 0.05c | 0.79 ± 0.07b |
| *Ash 12.5* | 0.66 ± 0.04c | 0.98 ± 0.08a |
| *Ash 25* | 0.68 ± 0.05bc | 0.93 ± 0.06a |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.0001 level; means separated using Fisher's Protected LSD Test

In treatments containing nitrogen fertilizer, treatment and year had significant effects on grain and oilseed yield in this study (Table 18).

**Table 18. Probability of F values for grain and oilseed yield for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with N – fertilizer (1998 – 2000).**

| | | *Grain / Oilseed Yield (t $ha^{-1}$)* | | |
|---|---|---|---|---|
| | | *'AC Lacombe' Barley* | *'Harrington' Barley* | *'Maverick' Canola* |
| *Source* | *df* | *Probability* | | |
| *Total* | *143* | | | |
| *Rep* | *2* | n/s | n/s | *** |
| *Treat* | *3* | **** | **** | **** |
| *Year* | *2* | *** | **** | **** |
| *Treat*Year* | *6* | ** | n/s | n/s |
| *Residual* | *130* | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

Only 'AC Lacombe' barley grain yield was significantly influenced by treatment-by-year interactions. Increases in 'AC Lacombe' grain yield ranged from 39 to 50%, -3 to 21%, and 3 to 18% respectively in 1998, 1999, and 2000 as a result of wood ash applications alone (Figure 5). The 25 t $ha^{-1}$ rate significantly increased grain yield, in all three years, over the control (Figure 5). Average grain yield of 'AC Lacombe' was significantly less in 1999 (3.82 ± 0.11 t $ha^{-1}$) and 2000 (4.02 ± 0.13 t $ha^{-1}$) than yields observed in 1998 (4.46 ± 0.13 t $ha^{-1}$); no significant differences were observed between 1999 and 2000. No significant differences were observed between the 12.5 and 25 t $ha^{-1}$, which consistently showed significantly larger grain yields compared to the N – control in all three years (Table 49).

Treatment and year significantly affected the grain and oilseed yield for 'Harrington' barley and 'Maverick' canola; no significant treatment-by-year interactions were observed for either crop (Table 18). Seed yield for 'Harrington' barley grain (Table 19) and 'Maverick' canola oilseed (Table 20) showed significant increases in all plots containing ash treatments, compared to the control.

Average increases in 'Harrington' grain yield of 20 to 32% were observed as a result of ash applications in plots with N – fertilizer from 1998 to 2000 (Table 19). Significant differences in yield were observed among all of the years. Average 'Harrington' barley grain yield in 1998 (4.03 ± 0.11 t $ha^{-1}$) was significantly greater than 1999 (3.46 ± 0.11 t $ha^{-1}$) that was significantly greater than 2000 (2.38 ± 0.06 t $ha^{-1}$).

**Table 19. *H. vulgare* L. cv. 'Harrington' data shown are average yield from a 9-$m^2$ area harvested from 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments in plots with N – fertilizer (1998 – 2000).**

| *Treatment (t $ha^{-1}$)* | *Grain Yield (t $ha^{-1}$ ± SE)* |
|---|---|
| *Control* | 2.74 ± 0.14c |
| *Ash 6* | 3.29 ± 0.14b |
| *Ash 12.5* | 3.62 ± 0.15a |
| *Ash 25* | 3.40 ± 0.16ab |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.0001 level; means separated using Fisher's Protected LSD Test

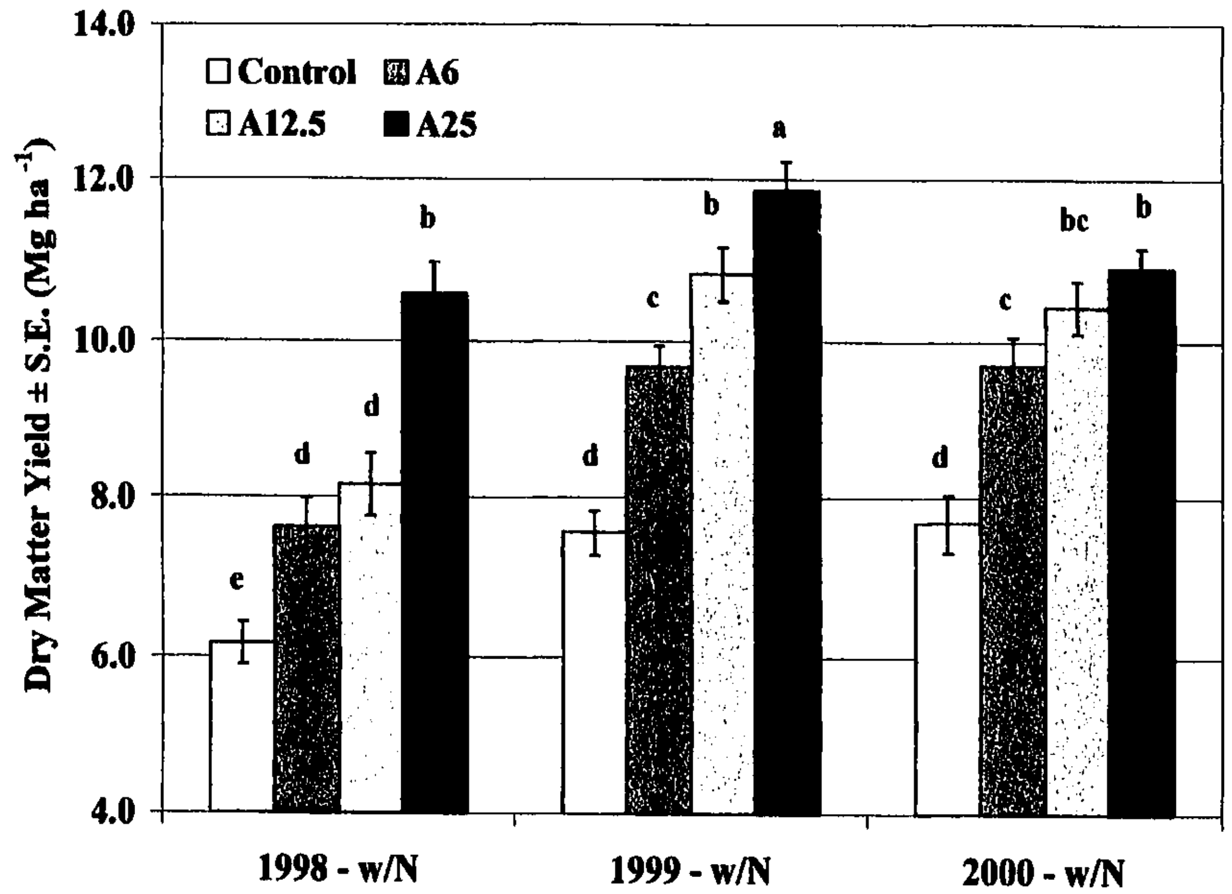

Figure 5. *H. vulgare* L. cv. 'AC Lacombe' grain yield, results shown are the averages of 9-m$^2$ areas harvested to determine yield from plots containing 6 (A6), 12.5 (A12.5), and 25 (A25) t ha$^{-1}$ wood ash and control treatments with N - fertilizer (1998 – 2000). Columns with the same letter are not significantly different at the P=0.01 level; means separated using Fisher's Protected LSD Test.

A similar trend was observed for 'Maverick' canola oilseed yield with 1998 (1.85 ± 0.08 t ha$^{-1}$) significantly greater than 1999 (1.09 ± 0.06 t ha$^{-1}$) that was significantly greater than 2000 (0.50 ± 0.03 t ha$^{-1}$). Average increases of 51 to 70% were observed in plots with N – fertilizer as a result of ash applications for 'Maverick' canola oilseed yield (Table 20).

**Table 20. *B. rapa* L. cv. 'Maverick' data shown are average yield from a 9-m$^2$ area harvested from 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments in plots with N – fertilizer (1998 – 2000).**

| *Treatment (t ha$^{-1}$)* | *Oilseed Yield (t ha$^{-1}$ ± SE)* |
|---|---|
| *Control* | 0.79 ± 0.10c |
| *Ash 6* | 1.19 ± 0.11b |
| *Ash 12.5* | 1.34 ± 0.12a |
| *Ash 25* | 1.26 ± 0.12ab |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.0001 level; means separated using Fisher's Protected LSD Test

Data collected in 1999 and 2000 from unfertilized plots showed that the only year had a significant impact on grain yield for 'AC Lacombe' and 'Harrington' barley as well as 'Maverick' canola oilseed yield (Table 21). Grain and oilseed yield was significantly greater for all three crops

**Table 21. Probability of F values for grain and oilseed yield for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots without N – fertilizer (1998 - 2000).**

| | | *Grain / Oilseed Yield (t ha$^{-1}$)* | | |
|---|---|---|---|---|
| | | *'AC Lacombe' Barley* | *'Harrington' Barley* | *'Maverick' Canola* |
| *Source* | *df* | | *Probability* | |
| ***Total*** | *95* | | | |
| ***Rep*** | *2* | n/s | * | n/s |
| ***Treat*** | *3* | n/s | n/s | n/s |
| ***Year*** | *1* | *** | **** | **** |
| ***Treat*Year*** | *3* | n/s | n/s | n/s |
| ***Residual*** | *86* | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

in 1999 than in 2000. Grain yield of 'AC Lacombe' was significantly greater in 1999 (2.67 ± 0.08 t ha$^{-1}$) than in 2000 (2.27 ± 0.06 t ha$^{-1}$); 'Harrington' yield was greater in 1999 (2.51 ± 0.05 t ha$^{-1}$) than in 2000 (1.63 ± 0.06 t ha$^{-1}$); and 'Maverick' yield was significantly greater in 1999 (0.82 ± 0.02 t ha$^{-1}$) than in 2000 (0.49 ± 0.02 t ha$^{-1}$).

### 3.6. Discussion

The present study was designed to determine the effect of wood ash applications on the productivity of barley and canola under field conditions and to determine the length of time a single wood ash application affected site productivity. As a result no attempt was made to separate the liming effect from the nutrient value of the wood ash. Generally, wood ash has a high pH and also contains levels of B, Ca, K, Mg, P, S, Zn and other elements essential for plant growth (Vance, 1996; Meyers and Kopecky, 1998). The elemental concentration and high pH of the wood ash provide an alternative liming agent for acidic soils and nutrient supplement for crop growth that benefits agricultural production (Erich, 1991; Naylor and Schmidt, 1989; Meyers and Kopecky, 1998). The addition of wood ash to the Gray Luvisolic soil used in the present field study increased productivity at the site. This study indicated that application of wood ash increased grain yield of two types of barley and canola cultivars. Wood ash applications had benefited agricultural crop growth with increases observed in total dry matter production and grain yield. Nitrogen fertilizer added with ash applications further increased the dry matter production and grain yield for each crop significantly over the period of the study.

Weather may also have played a significant role influencing the productivity of the three crops in this study. Average monthly temperatures over the study period (1998 – 2000) were very similar to the 40-year average for the area (Appendix B: Table 43 and Figure 9). However, the average monthly precipitation was not similar to the long – term average (Appendix B: Table 42 and Figure 8). Total precipitation during the study period was 32, 15, and 24% lower than the long – term 40-year average in 1998, 1999, and 2000, respectively. The reduced levels of precipitation during this period may have reduced the production capability at this site.

### *3.6.1. Barley Grain and Oilseed Yield*

Grain and seed yield for barley and canola over the three-year period increased due to wood ash applications. In the last two years of the study there was no significant benefit to grain or oilseed yield in plots containing only ash and no N – fertilizer. We also found that there were no significant differences among nitrogen – ash amended trials containing applications of 12.5 and 25 t $ha^{-1}$ in all three crops. This trend was also evident in last two years in comparisons among ash treatments with and without N – fertilizer.

### *3.6.2. Barley Dry Matter Production*

Increased dry matter production could be obtained over the long - term as a result of single ash applications comparable to other studies for alfalfa (Naylor and Schmidt, 1986, Naylor and Schmidt, 1989; Meyers and Kopecky, 1998), barley (Meyers and Kopecky, 1998; Bertschi, 2000), oats (Krejsl and Scanlon, 1996), and wheat (Etiegni et al., 1991a).

In our study, differences in dry matter production and grain yield, between wood ash applications of 12.5 and 25 t $ha^{-1}$, were often not significant suggesting maximum returns could be obtained at rates around 12.5 t $ha^{-1}$. This is supported by Naylor and Schmidt (1989) who found little benefit in applying higher rates of ash; although greater rates may provide longer term benefits to production. The authors found yield differences, over a two-year period, at rates between 11.7 and 17 t $ha^{-1}$ to be minimal; yields in the study were lower at 22.6 t $ha^{-1}$ than at 11.7 and 17 t $ha^{-1}$. This was found in our study as only slight increases in dry matter production were observed between 12.5 and 25 t $ha^{-1}$ applications. Higher applications of ash (25 t $ha^{-1}$) may provide a longer benefit to production than lower rates (6 and 12.5 t $ha^{-1}$), however a longer study would be required to support this statement.

### *3.6.3. Future Studies: Wood Ash and Crop Productivity*

Increased grain production would require fertilizer inputs, however, further studies are required to determine the effects of ash applications and commercial fertilizers on cereal grain and oilseed production before this statement can be supported. Results from this study can be used to help develop ash management strategies for agricultural production or to provide a starting point for future research projects involving ash applications. Field studies, like this project, and many others have been conducted using wood ash thoroughly incorporated into the soil profile. A unique challenge for the utilization of wood ash is posed as producers gradually move away from conventional tillage methods to management practices such as direct seeding or minimal tillage. Levels or depths of wood ash incorporation, and the resulting effects on crop growth and development, needs to be better understood to allow for wood ash use under these new management practices. Secondly, the liming effectiveness of wood ash has been well documented in many studies; however, little is known about the availability of the nutrients contained within the ash under field conditions. Wood ash contains low levels of nutrients like P, K, S, Ca, Mg, and numerous micronutrients all essential elements for plant growth. The availability of these nutrients to plants is not well documented, and should be evaluated to maximize the benefits of wood ash application on the productivity of agricultural crops.

### 3.7. Conclusion

Wood ash applications at rates up to 25 t ha$^{-1}$ had a significant impact on barley dry matter production, and the grain and oilseed yield of barley and canola. Increases in both dry matter and grain yield were still observed even with the lack of precipitation received during the study period. Nitrogen fertilizer added along with ash applications further enhanced both barley dry matter and the grain yield of all three crops from 1998 to 2000. No significant benefit in grain or oilseed yield was observed in 1999 or 2000 in trials containing only wood ash applications (i.e. without nitrogen fertilizer). However, this was not the case for barley dry matter yield as significant increases were still observed even without N – fertilizer. Results of this study also suggested that there was no significant benefit in the short term (i.e. 3 years) between applications of 12.5 and 25 t ha$^{-1}$ of wood ash.

Positive responses in total dry matter, grain and oilseed yield were observed for three years subsequent to one ash application. The results of this study show that wood ash application can improve agricultural production, and if managed properly can be a sustainable alternative with many economic and environmental benefits.

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# *CHAPTER FOUR: ELEMENTAL UPTAKE*

## 4. EFFECT OF WOOD ASH APPLICATIONS ON THE NUTRIENT AND METAL UPTAKE BY BARLEY (*HORDEUM VULGARE* L. CV.) AND BY CANOLA (*BRASSICA RAPA* L.)

### 4.1. Introduction

The addition of wood ash in one form or another to soil has been done for centuries through the burning of agricultural residues and the clearing of forested lands (Hopkins, 1910; Giovannini et al., 1993). Only in recent years has research begun to focus on the land application of wood ash, as this becomes an increasingly more favourable method of disposal. As guidelines pertaining to waste disposal become more restrictive and disposal costs become prohibitive, industry is beginning to look at alternative means to dispose of by-products, such as wood ash. The forest sector is addressing this issue by developing research programs to evaluate the feasibility of applying wood ash and other wood residues and by-products to agricultural land. Wood ash is produced by many wood-burning facilities; cogeneration systems that generate electricity, heat, and steam through the combustion of wood residues (bark, knots, etc.), and in the process generate the waste by-product, wood ash.

Studies in Europe and the United States have focused on the effects wood ash applications have on soil chemistry, plant growth, and the uptake of various nutrients and metals by plant tissue (Karsisto, 1972; Vance, 1996). Wood ash is of primary interest because of its dual characteristics. It is a suitable alternative to agricultural lime; and also contains various nutrients and trace elements essential for plant productivity. Plant uptake of essential elements is a necessary requirement in order for plants to develop fully. However, in addition to taking up essential elements for growth plants also take up other elements that are toxic to animals, humans, and even the plants themselves.

Studies have been conducted both in the greenhouse and the field on crops such as oats (*Avena sativa* L. – Krejsl and Scanlon, 1996); beans (*Phaseolus vulgaris* L. – Lerner and Utzinger, 1986; Krejsl and Scanlon, 1996); wheat (*Triticum aestivum* L. – Huang et al., 1993; Etiegni et al., 1991b); corn (*Zea mays* – Erich, 1991); barley (*Hordeum vulgare* L. – Meyers and Kopecky, 1998); and alfalfa (*Medicago sativa* L. – Naylor and Schmidt, 1989; Muse and Mitchell, 1995; Meyers and Kopecky, 1998). Studies have evaluated environmental concerns related to nutrient and trace metal uptake by plants within ash amended soils (Naylor and Schmidt, 1989; Muse and Mitchell, 1995; Mitchell and Black, 1997; Lickacz et al., 1998; Meyers and Kopecky, 1998). These authors found applications of wood ash increased dry matter production, and in some cases improvements in nutrient quality (Table 1), attributing growth increases to the chemical composition of the wood ash.

Campbell (1990) stated that chemical characteristics (Table 2) of wood ash are highly variable among coniferous and deciduous tree species and even influenced by the part of the tree (bark, leaves, wood, etc). In addition, applications of ash can provide a suitable liming agent while also serving as a source of nutrients (P, K, S, Ca, and Mg) and trace elements (B, Fe, and Zn) for agricultural crops (Lerner and Utzinger, 1986; Naylor and Schmidt, 1989; Etiegni et al., 1991a; Muse and Mitchell, 1995; Meyers and Kopecky, 1998). Hatch and Pepin (1985) suggested that four tonnes of ash is equivalent to one tonne of agricultural limestone, based on the $CaCO_3$ equivalence of wood ash. The increase in both soil pH and elemental concentration after wood ash applications has been well documented. Studies have reported wood ash applications increased soil pH by 0.5 to 1.5 units (Naylor and Schmidt, 1989; Ohno and Erich, 1990; Etiegni et al., 1991a; Muse and Mitchell, 1995; Meyers and Kopecky, 1998).

Soils within the Luvisolic soil region of Alberta have a low pH and often tend to be deficient in some essential elements required for plant growth (Alberta Agriculture, 1992; Alberta Agriculture, 1996).

Low pH levels may result in the increased availability of some metals (Wolf, 1990). Metals like B, Cd, and Zn in low pH soils can be phytotoxic, resulting in reduced productivity and yields. Quite often as a remedy, agricultural lime is added to increase soil pH and reduce the availability of metals such as B (Gupta, 1977) and Cd (Gavi et al., 1997; Grant et al., 1998). However, the use of agricultural lime in many regions of Alberta is often limited by economics and logististics; therefore alternative liming agents are being evaluated.

Wood ash is one alternative that has drawn the attention of the agricultural community. In addition to serving as a liming agent wood ash also contains many elements essential for plant growth (Vance, 1996; Naylor and Schmidt, 1989). These include macronutrients such as Ca, P, K, Mg, and S in addition to many trace elements like B and Zn as well as heavy metals like Cd. The levels of B, Cd, and Zn within the ash were of main concern, since they can accumulate within the soil and in high concentrations can cause phytoxic reactions in plants or bioaccumulate within plant, animal, or human tissues.

Applying lime to increase the pH of acidic soils can reduce B and Cd levels in the soil. This has the potential to reduce the chances of B toxicity or Cd uptake in many agricultural crops (Gupta, 1977; Gupta et al., 1985). Boron toxicity often occurs at 200 ppm within the dry matter of the plant tissue and deficiencies occur at B levels less than 15 ppm (NRC, 1980; Gupta et al., 1985). Boron levels in many Gray Luvisols are often deficient for adequate growth of canola (Nuttal et al 1987).

Cadmium is recognized as an environmental problem with serious implications. Cadmium, a heavy metal, if ingested at 'moderate' amounts can bioaccumulate within the body often leading to health problems like anemia, bone de-mineralization, and can result in liver and kidney damage (NRC, 1980). The NRC (1980) of Canada suggests that Cd plays an antagonistic role against other essential trace elements like Cu, Fe, Zn, and the macronutrient Ca. Cadmium limits of 0.1 mg $kg^{-1}$

placed on cereal grain and oilseeds being traded in the international market are being discussed (Grant et al. 1998).

Zinc is a trace element that plays an important role in enzymatic functions within the plant. However, Zn at high concentrations within the soil can cause phytotoxicity (Wolf, 1990). Zinc toxicity in agricultural crops is often the result of high applications of municipal and / or industrial biosolids; Zn availability can be reduced by liming soils to increase soil pH (Pepper et al., 1983; Wolf, 1990). Zinc deficiencies are one of the most common nutrient deficiencies in agricultural soils and can be corrected with applications of Zn fertilizers (Lindsay, 1972).

## 4.2. Objectives

The objective of the field study were:

1. To assess the effect of supplemental wood ash applications on crop quality specifically the uptake of nutrients and metals by the crop, specifically B, Cd, and Zn.
2. Determine the duration that these and other elements added through wood ash applications are available for plant uptake.

## 4.3. Methods and Materials

### *4.3.1. Study Design*

A randomized complete block design, using three replications, was used for the study. Four wood ash loading rates (control (0), 6, 12.5 and 25 t $ha^{-1}$) were used as treatments in this experiment. The quarter section of land used in our experiment was under continuous cropping before the study began, and is located in the Luvisolic soil zone (Appendix A - Figure 6). The site located at SE1/4 22-68-19W4 was divided into three blocks in the NE, NW, and SE portion of the section (Appendix A - Figure 7). Plot sizes in the NW and SE areas of the quarter were 50-m wide by 300-ms long while plots in the NE area were 30-m wide and 250-m long. Separation of the crops and wood ash treatments in the study was accomplished using a 3-m buffer zone between the plots. The buffer zone was rotovated twice during each year to a depth of 0.2 meters. Wood ash plots were further divided into three sections to allow seeding of canola and two barley cultivars. Crops were seeded perpendicular to wood ash and nitrogen applications.

### *4.3.2. Ash*

The mill supplying the wood ash for this study operates a power boiler fueled by wood waste and natural gas producing about 16, 000 tonnes of wood ash annually through the incineration of wood waste as fuel for the generation of heat for pulp production. The wood ash has been characterized extensively for physical characteristics, available nutrients, total nutrients, available metals, and total metals (Appendix D). Wood ash was stockpiled on-site in SE1/4 22-68-19W4 prior to application between March 1998 to mid-May 1998. Ash was then applied to the soil during the last week of May in 1998 using a side discharge GEHL Scavenger Manure Spreader (Appendix E), calibrated to apply wood ash at 6, 12.5 and 25 t $ha^{-1}$. After application the ash was incorporated, by disc, to a depth of 0.2-m and allowed to incubate 5 days before seeding occurred at the end of May in 1998.

### *4.3.3. Soils*

The site of the field trial was located at SE1/4 22-68-19W4, approximately 25 km NW of Boyle, AB, in Orthic Gray Luvisol soils (Appendix A - Figure 6). The site is complex in nature with a classification of 80% Tolman, 10% Tawatinaw, and 10% Amisk soils with a gently undulating slope of 2% to 4% (Report No. 29, 1972). Amisk soil groups are part of the Degraded

Brunisols, while, both the Tolman and Tawatinaw groups belong to the Orthic Gray Luvisols. The soil horizons are Ae, Bt, and Ck with silt loam texture and moderately acidic pH from 5.5 to 6 (Report No. 29, 1972). The main soil group consisted of Tolman soils that have developed on alluvial lacustrine well-drained parent material. Tolman soils developed under forest vegetation and consisted of primarily hardwood species such as aspen, poplar, and white birch.

### *4.3.4. Crops*

A Polish canola and two barley cultivars were chosen for these studies as both are commonly grown throughout the Prairie Provinces of Canada and are valuable crops in Alberta (Agrium, 1997). Six row 'AC Lacombe' barley (Kibite, 1993), two row 'Harrington' barley (Harvey and Rossnagel, 1984), and 'Maverick' canola were chosen because they are considered short season cultivars and are commonly grown in the study area. 'AC Lacombe' barley is commonly used for silage and feed grain and 'Harrington' barley is mainly used in malting. Crops were seeded in the last week of May in all three years. Barley was seeded at a rate of 112 kg ha$^{-1}$ using a John Deere Air Seeder, and the Polish canola cultivar 'Maverick' was seeded at 7.8 kg ha$^{-1}$ using a Valmar Airflo seeder. Crops were seeded in the same location for all three years of the study. Additional urea (46-0-0) fertilizer was banded in half of each plot to provide 130 kg ha$^{-1}$ (56 kg ha$^{-1}$ 1998; 103 kg ha$^{-1}$ 1999; 108 kg ha$^{-1}$ 2000) of nitrogen based on soil fertility analysis. Weed control, in 1998, within the barley was done in early-July by spraying using Refine Extra$^{\text{TM}}$ and Assert$^{\text{TM}}$. In canola, weed control was done by using the pre-emergent herbicide Edge$^{\text{TM}}$ and later by spraying Lontrel 360$^{\text{TM}}$ along with Poast Ultra$^{\text{TM}}$ and Merge$^{\text{TM}}$. A pre-harvest application of Round-up$^{\text{TM}}$ was applied, in early-September of 1998, for dessication. Similar weed control measures were undertaken in 1999 and 2000, but the pre-harvest dessication in early-September was not done.

Dry matter was determined on barley at the 'soft dough' stage (before ripening occurred) after 70, 72, and 72 days after seeding in 1998, 1999, and 2000 respectively. Dry matter for 'AC Lacombe' barley was determined in all three years, while on 'Harrington' barley it was determined during the last two years. Randomly selected whole plant samples were taken from 0.25-m$^2$ (n=30: 'AC Lacombe'; n=6: 'Harrington') for the two barley cultivars by clipping them 5–cm above the ground. All three crops were sampled to determine grain yield at maturity 107 days (1998), 103 days (1999), and 105 days (2000) after seeding occurred. Weeds were separated at the site and removed from each sample. Weed control was good in 1998 and 1999, however wild oats and buckwheat were present in 2000 in the field plots. Weed populations comprised approximately 5% of 'Harrington' barley and approximately 2% of 'AC Lacombe' plots. However, all plots in each of the replications were relatively similar. Similar observations were made for 'Maverick' canola plots that contained buckwheat. In all three years samples were collected and dried at 55°C for six days; only the nitrogen control plots were sampled in 1998. After drying, dry matter weight was determined, and samples sent for plant tissue analysis to EnviroTest Laboratories (Calgary, AB).

An independent research company, Gateway Research Organization (GRO) Westlock AB, harvested grain and oilseed samples using a Wintersteiger Nurserymaster Elite combine. Seed yield was determined from randomly selected standard 9-m$^2$ areas (1.5-m wide by 6-m long). Samples (n=12) were taken from each of the crops in N – fertilized and unfertilized areas for each plot. Only the N – fertilized plot was sampled from the control in 1998; samples were collected and dried at 55°C for three days. Sub-samples of grain and oilseed samples were sent to EnviroTest Laboratories (Calgary, AB) for chemical analysis. Remaining samples were sent to GRO to be cleaned and for seed yield determination. Seed cleaning was done using an Almaco Seed Cleaner (Allan Machine Company, Nevada, IA).

Barley tissue, barley grain, and oilseed samples were sent to EnviroTest Laboratories (Calgary, AB) for chemical analysis. Samples were analyzed for N, P, K, S, B, Ca, Cd, Cu, Fe, Mg, Mn, and Zn. Barley tissue and grain samples from nitrogen – ash amended ('AC Lacombe' tissue & grain: n=12; 'Harrington' grain: n=3; 'Maverick' oilseed: n=12) and ash (All crops: n=3) amended plots were analyzed from each of the three replications. For chemical analysis, whole plants and cereal grains were dried at 65°C and ground into a powder using a small coffee grinder (plant samples) and small coffee mill (cereal grains); oilseed samples were not ground. The tissue was digested using a modified EPA 3050 consisting of a nitric and hydrochloric acid digestion to dissolve the metals (B, Ca, Cd, Cu, Fe, K, Mg, Mn, P, S, and Zn); hydrogen peroxide was added to break down any organics. Analysis of the digest was then done by ICP-AES. Further analysis of Cd was done at a low detection limit for cereal grains and oilseed samples; this was done using the EPA 3051 digestion, with analysis done by ICP-MS to obtain a detection limit of 0.08 mg $kg^{-1}$. Nitrogen analysis of the samples was conducted using a Kjeldahl digestion; by mixing the sample with sulphuric acid, catalysts, and hydrogen peroxide and then heating to 390°C to convert all plant tissue nitrogen into the ammonium form. Analysis of the ammonium was conducted by a Technicon Autoanlyzer to provide Total Nitrogen within the sample (NAQUADAT no. 07021).

Oilseed quality analysis was performed by the Canadian Grain Commission's Grain Research Laboratory (Winnipeg, MB) on samples (n=3) from control and ash amended plots containing N – fertilizer. Oilseed samples for each of the three years were analyzed for protein, oil, chlorophyll content, and glucosinolate content by Near Infrared Spectroscopy (NIR), while protein content was determined using a LECO FP-428 Nitrogen Determinator (Canadian Grain Commission, 1998). Results for oil, chlorophyll, and glucosinolate content are expressed on an 8.5% moisture basis.

### *4.3.5. Climatic Data*

Climatic factors, temperature and precipitation, play a significant role in the development and productivity of all agricultural crops. The Athabasca region typically receives approximately 500-mm of total precipitation annually based the 40-year (1959 to 1999) average (Environment Canada data). Precipitation data (Appendix B: Table 42 & Figure 8) obtained from Environment Canada showed that during the years the study period (1998 – 2000) the level of precipitation in the area was 32, 15, and 24% lower than the 40-year average. The average temperature from May to August during the course of the study was very similar to the 40-year average for the area (Appendix B: Table 43 & Figure 9).

### *4.3.6. Statistical Analysis*

Tests to satisfy assumptions set by the ANOVA test were conducted and were supported. Analysis of variance was conducted on data collected for dry matter and grain yield using the statistical program AGROBASE™ 99 (Agronomix, 1999). Statistical differences determined among means were then separated using Fisher's Protected Least Significant Difference (LSD) test at the $P=0.05$, $P=0.01$, $P=0.001$, and $P=0.0001$ levels.

## 4.4. Results:

### *4.4.1. Cadmium*

Cadmium analysis, from plots with and without N – fertilizer, of 'AC Lacombe' barley tissue remained below the detection limit of 1 mg kg$^{-1}$, while analysis of grain and oilseed samples were below 0.08 mg kg$^{-1}$ for the control (no ash treatment) and 25 t ha$^{-1}$ ash plots (Table 22). Cadmium levels were below 1.0 mg kg$^{-1}$ for 6 and 12.5 t ha$^{-1}$ ash plots. These low values did not warrant further statistical comparison among samples.

**Table 22. Cadmium levels (mg kg$^{-1}$) in tissue, grain, and oilseed samples collected from 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments in plots with and without N – fertilizer.**

| | *Plots With Nitrogen Fertilizer (1998 – 2000)* | | | |
|---|---|---|---|---|
| | *'AC Lacombe' Barley* | | *'Harrington' Barley* | *'Maverick' Canola* |
| *Treatment (t ha$^{-1}$)* | *Grain* | *Tissue* | *Grain* | *Oilseed* |
| *Control* | <0.08 | <1 | <0.08 | <0.08 |
| *Ash 6* | <1 | <1 | <1 | <1 |
| *Ash 12.5* | <1 | <1 | <1 | <1 |
| *Ash 25* | <0.08 | <1 | <0.08 | <0.08 |

| | *Plots Without Nitrogen Fertilizer (1999 – 2000)* | | | |
|---|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *Grain* | *Tissue* | *Grain* | *Oilseed* |
| *Control* | <0.08 | <1 | <0.08 | <0.08 |
| *Ash 6* | <1 | <1 | <1 | <1 |
| *Ash 12.5* | <1 | <1 | <1 | <1 |
| *Ash 25* | <0.08 | <1 | <0.08 | <0.08 |

### *4.4.2. Nutrient Uptake – 'AC Lacombe' Barley*

Treatment, year, and treatment-by-year interaction had significant impacts on the nutrient quality of 'AC Lacombe' barley tissue and grain (Table 23 to Table 24). Significant differences in nutrient quality were observed in samples collected from trials with or without N – fertilizer.

Year crops were grown had a significant influence on the nutrient content of 'AC Lacombe' tissue and grain (Appendix C - Table 50 and Table 51) in samples collected from areas fertilized with nitrogen fertilizer. 'AC Lacombe' barley tissue had significantly greater levels of P, S, and B in the first year of the study (Appendix C - Table 50) while, K and Ca were significantly greater in the first and last year and Mg content was significantly greater in the first two years (Table 50). Boron, Fe, and Zn content of 'AC Lacombe' barley grain (Appendix C - Table 51) was significantly greater in the

**Table 23. Probability of F values of 'AC Lacombe' barley tissue N, P, K, S, B, Ca, Cu, Fe, Mg, Mn, and Zn nutrient analysis results of for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with and without N – fertilizer.**

| | | *Plots With Nitrogen Fertilizer (1998 – 2000)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *'AC Lacombe'* | *df* | *N* | *P* | *K* | *S* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | | | | | | *Probability* | | | | | |
| *Total* | *143* | | | | | | | | | | | |
| *Rep* | *2* | n/s | **** | * | ** | ** | n/s | ** | n/s | * | **** | * |
| *Treat* | *3* | ** | *** | **** | **** | n/s | **** | n/s | n/s | ** | * | n/s |
| *Year* | *2* | **** | **** | **** | **** | **** | **** | **** | **** | **** | n/s | *** |
| *Treat*Year* | *6* | n/s | n/s | n/s | n/s | n/s | n/s | * | * | n/s | n/s | * |
| *Residual* | *130* | | | | | | | | | | | |

| | | *Plots Without Nitrogen Fertilizer (1999 – 2000)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *df* | *N* | *P* | *K* | *S* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | | | | | | *Probability* | | | | | |
| *Total* | 23 | | | | | | | | | | | |
| *Rep* | 2 | n/s | n/s | n/s | n/s | * | n/s | n/s | n/s | n/s | n/s | n/s |
| *Treat* | 3 | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s |
| *Year* | 1 | ** | * | ** | n/s | ** | n/s | ** | n/s | *** | * | n/s |
| *Treat*Year* | 3 | n/s | n/s | n/s | * | n/s | n/s | n/s | n/s | n/s | n/s | n/s |
| *Residual* | 14 | | | | | | | | | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

**Table 24. Probability of F values of 'AC Lacombe' barley grain N, P, K, S, B, Ca, Cu, Fe, Mg, Mn, and Zn nutrient analysis results of for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with and without N – fertilizer.**

| | | *Plots With Nitrogen Fertilizer (1998 – 2000)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *'AC Lacombe'* | *df* | *N* | *P* | *K* | *S* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | *Probability* | | | | | | | | | | |
| *Total* | 143 | | | | | | | | | | | |
| *Rep* | 2 | n/s | n/s | **** | *** | * | *** | **** | **** | n/s | **** | **** |
| *Treat* | 3 | * | n/s | **** | **** | * | n/s | **** | n/s | n/s | n/s | n/s |
| *Year* | 2 | ** | ** | **** | n/s | **** | n/s | **** | **** | n/s | **** | ** |
| *Treat*Year* | 6 | * | n/s | *** | n/s | n/s | n/s | **** | n/s | n/s | n/s | n/s |
| *Residual* | 130 | | | | | | | | | | | |

| | | *Plots Without Nitrogen Fertilizer (1999 – 2000)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *df* | *N* | *P* | *K* | *S* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | *Probability* | | | | | | | | | | |
| *Total* | *23* | | | | | | | | | | | |
| *Rep* | *2* | n/s | * | n/s | n/s | n/s | n/s | * | * | n/s | *** | * |
| *Treat* | *3* | n/s | n/s | n/s | * | n/s | n/s | n/s | * | n/s | n/s | ** |
| *Year* | *1* | * | ** | ** | n/s | * | *** | n/s | **** | ** | n/s | n/s |
| *Treat*Year* | *3* | n/s | n/s | * | * | n/s | n/s | n/s | n/s | n/s | * | * |
| *Residual* | *14* | | | | | | | | | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

second year of the study (1999). Phosphorus was significantly greater in the last year (2000), and Mn in the first year (1998).

Year crops were grown also had a significant impact on the nutrient content of samples collected from areas without the nitrogen fertilizer for 'AC Lacombe' tissue and grain (Appendix C: Table 52 and Table 53). 'AC Lacombe' barley tissue (Appendix C - Table 52) levels of N, P, K, Cu and Mn were significantly greater in the last year of the study (2000). Boron content was significantly greater in the second year (1999). Nitrogen, P, K, Cu, and Mn content of 'AC Lacombe' tissue (Appendix C - Table 52) and N, P, and Ca content of 'AC Lacombe' grain (Table 53) was greater in the last year (2000). Boron content of the tissue and Mg, B, and Fe in the grain was greater in the second year (1999) for 'AC Lacombe'.

Treatment effect had a significant impact on the nutrient content of 'AC Lacombe' barley tissue (Table 23) and grain (Table 24) in plots containing N – fertilizer. Average concentrations of N, P, Ca, Mg, and Mn in 'AC Lacombe' tissue were lower in the 25 t ha$^{-1}$ treatment than the control from 1998 to 2000 (Table 25). Levels of K and S levels in 'AC Lacombe' tissue were significantly higher in 12.5 and 25 t ha$^{-1}$ ash treatments (Table 25). The B levels within 'AC Lacombe' grain were significantly lower in the 12.5 and 25 t ha$^{-1}$ treatments than in the control during the study period (Table 26). There was no significant difference between these two ash treatments. The average S content of 'AC Lacombe' grain was significantly greater in samples taken from plots containing wood ash treatments from 1998 to 2000 (Table 26).

Treatment also had a significant influence on the nutrient composition of grain samples collected from unfertilized plots. Average Fe content of 'AC Lacombe' grain was significantly greater in samples from collected from plots amended with 6 (44.50 ± 4.19 mg kg$^{-1}$) and 12.5 t ha$^{-1}$ (53.00 ± 7.97 mg kg$^{-1}$) of ash than the control (36.83 ± 3.83 mg kg$^{-1}$). There was

**Table 25. Average concentration of N, P, K, S, Ca, Mg, and Mn in 'AC Lacombe' barley tissue from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 - 2000).**

| | ------------ (% ± SE) | | | | | ------------ | (mg kg$^{-1}$ ± SE) |
|---|---|---|---|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *N* | *P* | *K* | *S* | *Ca* | *Mg* | *Mn* |
| *Control* | 1.54 ± 0.06a | 0.24 ± 0.01a | 1.31 ± 0.06c | 0.12 ± 0.01c | 0.48 ± 0.02a | 0.13 ± 0.00a | 15.82 ± 1.38a |
| *Ash 6* | 1.49 ± 0.05a | 0.19 ± 0.01b | 1.39 ± 0.05bc | 0.20 ± 0.01b | 0.43 ± 0.02b | 0.12 ± 0.00ab | 12.50 ± 0.69b |
| *Ash 12.5* | 1.45 ± 0.04a | 0.20 ± 0.01b | 1.49 ± 0.05b | 0.23 ± 0.01a | 0.41 ± 0.01b | 0.12 ± 0.00ab | 13.06 ± 0.77b |
| *Ash 25* | 1.34 ± 0.05b | 0.21 ± 0.01b | 1.62 ± 0.05a | 0.23 ± 0.01a | 0.38 ± 0.01c | 0.11 ± 0.00b | 12.32 ± 0.57b |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (Mn), P=0.01 (N & Mg), P=0.001 (P), and P=0.0001 (K & S) levels; means separated using Fisher's Protected LSD Test

**Table 26. Average concentration of B and S in 'AC Lacombe' grain from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 - 2000).**

| *Treatment (t ha$^{-1}$)* | *B (mg kg$^{-1}$ ± SE)* | *S (% ± SE)* |
|---|---|---|
| *Control* | 5.06 ± 0.67a | 0.30 ± 0.03b |
| *Ash 6* | 4.26 ± 0.35ab | 0.45 ± 0.02a |
| *Ash 12.5* | 3.59 ± 0.28b | 0.45 ± 0.02a |
| *Ash 25* | 3.66 ± 0.24b | 0.45 ± 0.03a |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (B) and P=0.0001 (S) levels; means separated using Fisher's Protected LSD Test no significant difference between the control and 25 t ha$^{-1}$ (43.17 ± 5.93 mg kg$^{-1}$) treatments.

Treatment-by-year interactions influenced the nutrient content of 'AC Lacombe' barley tissue (Table 23) and grain (Table 24) significantly in plots with N – fertilizer. Iron content of 'AC Lacombe' barley tissue was significantly greater in all treatment plots, containing N - fertilizer, in 1998 than in 1999 or 2000 (Table 27). Elevated levels of Zn in the barley tissue were observed after initial ash applications, however by the last year of the study levels in ash treatments were not different from the control (P>0.05) (Table 27). Copper was significantly lower in the last year of the study in the 25 t ha$^{-1}$ treatment, in plots with N – fertilizer.

**Table 27. Average concentration of Cu, Fe, and Zn over the three years of 'AC Lacombe' tissue from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| | *mg kg$^{-1}$ ± SE* | | |
|---|---|---|---|
| Treatment (t ha$^{-1}$) | Cu | Fe | Zn |
| *1998* | | | |
| *Control* | 6.86 ± 0.47a | 62.87 ± 6.28bc | 32.68 ± 1.89b |
| *Ash 6* | 5.10 ± 0.62a | 68.67 ± 4.60b | 28.46 ± 1.11cde |
| *Ash 12.5* | 7.33 ± 1.08a | 96.00 ± 20.02a | 38.74 ± 3.43a |
| *Ash 25* | 6.09 ± 0.50a | 67.50 ± 4.06b | 33.39 ± 2.47bc |
| *1999* | | | |
| *Control* | 2.92 ± 0.27a | 51.83 ± 5.43d | 33.24 ± 4.60bcd |
| *Ash 6* | 3.25 ± 0.14a | 45.25 ± 1.78def | 29.78 ± 1.32cde |
| *Ash 12.5* | 3.19 ± 0.12a | 42.20 ± 3.95ef | 29.71 ± 1.62cde |
| *Ash 25* | 3.41 ± 0.09a | 53.50 ± 3.11cd | 35.23 ± 1.88ab |
| *2000* | | | |
| *Control* | 3.28 ± 0.30a | 48.42 ± 5.75def | 28.98 ± 2.00cde |
| *Ash 6* | 4.18 ± 0.23a | 50.17 ± 5.25de | 28.28 ± 1.26de |
| *Ash 12.5* | 3.54 ± 0.24a | 48.25 ± 5.02def | 25.60 ± 0.94e |
| *Ash 25* | 2.98 ± 0.22b | 39.17 ± 1.96f | 25.03 ± 0.88e |

a-f Means and Standard error (SE) followed by the same letter are not significantly different at P=0.001 (Zn) and P=0.0001 (Cu & Fe) levels; means separated using Fisher's Protected LSD Test

Nitrogen content of 'AC Lacombe' grain was lowest in the 6 t ha$^{-1}$ plot in 1998 and 25 t ha$^{-1}$ ash applications in 1999 and 2000 (Table 28). Potassium content in 'AC Lacombe' grain was significantly greater in 25 t ha$^{-1}$ ash plots in 1998 and 2000, and 12.5 t ha$^{-1}$ plots in 1998 (Table 28). The Cu levels in 'AC Lacombe' barley grain was significantly lower in 1999 and 2000 than in 1998 in all treatment plots (Table 28).

**Table 28. Average concentration of N, K, and Cu over the three years of 'AC Lacombe' barley grain from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| Treatment (t ha$^{-1}$) | *(% ± SE)* | | *(mg kg$^{-1}$ ± SE)* |
|---|---|---|---|
| *1998* | *N* | *K* | Cu |
| *Control* | 1.95 ± 0.11bc | 0.57 ± 0.01b | 7.81 ± 0.30a |
| *Ash 6* | 1.65 ± 0.04e | 0.50 ± 0.01c | 4.82 ± 0.40c |
| *Ash 12.5* | 1.80 ± 0.04cde | 0.61 ± 0.01a | 7.39 ± 0.13ab |
| *Ash 25* | 1.79 ± 0.04cde | 0.61 ± 0.01a | 7.12 ± 0.16b |
| *1999* | | | |
| *Control* | 1.78 ± 0.08cd | 0.38 ± 0.02e | 3.83 ± 0.14d |
| *Ash 6* | 1.89 ± 0.08cd | 0.35 ± 0.01f | 3.73 ± 0.10d |
| *Ash 12.5* | 1.80 ± 0.06cde | 0.36 ± 0.01f | 3.80 ± 0.12d |
| *Ash 25* | 1.76 ± 0.12de | 0.38 ± 0.01e | 3.83 ± 0.15d |
| *2000* | | | |
| *Control* | 2.14 ± 0.07a | 0.39 ± 0.01e | 3.49 ± 0.33d |
| *Ash 6* | 2.12 ± 0.04ab | 0.37 ± 0.01ef | 3.98 ± 0.54d |
| *Ash 12.5* | 1.84 ± 0.09cd | 0.39 ± 0.01e | 3.99 ± 0.40d |
| *Ash 25* | 1.79 ± 0.09cde | 0.43 ± 0.02d | 3.63 ± 0.19d |

a-f Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (N), P=0.001 (K), and P=0.0001 (Cu) levels; means separated using Fisher's Protected LSD Test

A significant treatment-by-year interaction among plots without N – fertilizer was also evident within 'AC Lacombe' tissue (Table 23) and grain (Table 24). Sulphur content of 'AC Lacombe' tissue (Table 29) and grain (Table 29) was greater in the 12.5 t ha$^{-1}$ ash treatment in the second year (1999), but no differences were observed in the last year (2000) among the treatments. Manganese and Zn content in 'AC Lacombe' grain collected from plots containing 12.5 t ha$^{-1}$ of wood ash was significantly greater in 1999 than the control (Table 29), but no significant differences were observed in 2000. Zinc levels in 'AC Lacombe' grain (Table 29) were significantly lower in all trials in 2000 than in 1999, with the exception of the 12.5 t ha$^{-1}$. Potassium levels in 'AC Lacombe' grain in samples from the 25 t ha$^{-1}$ were only greater in the second year of the study (Table 29). The 12.5 t ha$^{-1}$ ash trial showed higher levels of Mn and Zn within 'AC Lacombe' grain (Table 29). Levels of Mn and Zn decreased over the two year period, and no significant differences were observed among treatments in the last year of the study.

### *4.4.3. Nutrient Removal by 'AC Lacombe' Barley*

Table 30 contains results from plots supplemented with nitrogen fertilizer for 'AC Lacombe' barley. 'AC Lacombe' barley seeded in plots containing applications of 6 to 25 t ha$^{-1}$ of wood ash removed 16-26% more N; 2-31% more P; 28-83% more K, and 87-150% more S than the nitrogen fertilized control (Table 32).

The information in Table 31 is for 'AC Lacombe' samples collected from unfertilized plots, analysis indicated 'AC Lacombe' barley seeded in plots with applications of 6 to 25 t ha$^{-1}$ of wood ash removed 2-16% more N; 17-46% more P; 11-41% more K, and 42-67% more S than the untreated control (Table 32).

### *4.4.4. Nutrient Uptake – ' Harrington' Barley*

Treatment, year, and treatment-by-year interactions had significant impacts on the nutrient quality of 'Harrington' barley grain (Table 33). Significant differences in nutrient quality were observed in samples collected from trials with or without N – fertilizer.

Year had a significant influence on the average nutrient content of 'Harrington' grain (Appendix C - Table 54 and Table 55) in samples collected from areas fertilized with N – fertilizer. Nitrogen and P content of 'Harrington' barley grain (Appendix C - Table 54) were significantly greater in the last year (2000) of the study, while Ca content was significantly greater in the second year (1999).

**Table 29. Average concentration of S in 'AC Lacombe' barley tissue and K, Mn, S, and Zn in 'AC Lacombe' barley grain from plots containing applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments without N – fertilizer (1999 - 2000).**

| | *% ± SE* | | | *(mg kg$^{-1}$ ± SE)* | |
|---|---|---|---|---|---|
| | *'AC Lacombe' Barley Tissue* | *'AC Lacombe' Barley Grain* | | *'AC Lacombe' Barley Grain* | |
| *Treatment (t ha$^{-1}$)* | *S* | *K* | *S* | *Mn* | *Zn* |
| *1999* | | | | | |
| *Control* | 0.10 ± 0.01c | 0.48 ± 0.04a | 0.10 ± 0.01c | 7.93 ± 0.91b | 23.10 ± 2.12d |
| *Ash 6* | 0.17 ± 0.02ab | 0.40 ± 0.02b | 0.11 ± 0.01bc | 9.43 ± 0.42a | 33.60 ± 1.15ab |
| *Ash 12.5* | 0.19 ± 0.04a | 0.39 ± 0.03b | 0.13 ± 0.00a | 10.60 ± 1.14a | 34.53 ± 1.92a |
| *Ash 25* | 0.19 ± 0.02a | 0.51 ± 0.02a | 0.11 ± 0.00bc | 7.57 ± 1.56b | 25.93 ± 2.59cd |
| *2000* | | | | | |
| *Control* | 0.16 ± 0.02ab | 0.38 ± 0.02b | 0.11 ± 0.00bc | 9.77 ± 1.40a | 28.43 ± 0.45c |
| *Ash 6* | 0.17 ± 0.01ab | 0.40 ± 0.02b | 0.12 ± 0.00ab | 9.13 ± 1.03a | 28.00 ± 1.51c |
| *Ash 12.5* | 0.14 ± 0.02bc | 0.40 ± 0.02b | 0.12 ± 0.00ab | 9.17 ± 1.43ab | 29.70 ± 2.93bc |
| *Ash 25* | 0.16 ± 0.01ab | 0.39 ± 0.02b | 0.12 ± 0.00ab | 9.97 ± 1.49a | 27.63 ± 2.72c |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 30. Nutrient uptake by 'AC Lacombe' barley in plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments, based on results collected from 1998 to 2000.**

| | *Grain Yield (t ha$^{-1}$)* | | | *Nutrient Content in Grain (%)* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *1998* | | | | *1999* | | | | *2000* | | | |
| | *1998* | *1999* | *2000* | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* |
| *Control* | 3.38 | 3.60 | 3.68 | 1.95 | 0.30 | 0.57 | 0.12 | 1.78 | 0.24 | 0.38 | 0.12 | 2.14 | 0.31 | 0.39 | 0.11 |
| *Ash 6* | 4.69 | 3.48 | 3.79 | 1.65 | 0.29 | 0.50 | 0.14 | 1.90 | 0.21 | 0.35 | 0.14 | 2.11 | 0.29 | 0.37 | 0.14 |
| *Ash 12* | 5.06 | 3.86 | 4.23 | 1.80 | 0.27 | 0.61 | 0.14 | 1.80 | 0.21 | 0.36 | 0.14 | 1.84 | 0.48 | 0.38 | 0.14 |
| *Ash 25* | 4.71 | 4.34 | 4.36 | 1.79 | 0.28 | 0.61 | 0.14 | 1.76 | 0.22 | 0.38 | 0.13 | 1.79 | 0.34 | 0.43 | 0.14 |

| | *Dry Matter Production (t ha$^{-1}$)* | | | *Nutrient Content in Tissue (%)* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | *1998* | | | | *1999* | | | | *2000* | | | |
| | *1998* | *1999* | *2000* | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* |
| *Control* | 6.18 | 7.55 | 7.68 | 1.35 | 0.27 | 1.42 | 0.14 | 1.41 | 0.19 | 1.10 | 0.11 | 1.87 | 0.27 | 1.43 | 0.11 |
| *Ash 6* | 7.61 | 9.68 | 9.70 | 1.28 | 0.22 | 1.56 | 0.25 | 1.40 | 0.15 | 1.12 | 0.18 | 1.79 | 0.21 | 1.47 | 0.18 |
| *Ash 12* | 8.15 | 10.80 | 10.40 | 1.37 | 0.25 | 1.57 | 0.28 | 1.30 | 0.14 | 1.32 | 0.18 | 1.66 | 0.21 | 1.57 | 0.21 |
| *Ash 25* | 10.60 | 11.90 | 10.90 | 1.30 | 0.25 | 1.69 | 0.28 | 1.13 | 0.17 | 1.42 | 0.2 | 1.58 | 0.21 | 1.74 | 0.21 |

**Table 31. Nutrient uptake by 'AC Lacombe' barley in plots without N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments, based on results collected from 1999 and 2000.**

| | *Grain Yield ($t\ ha^{-1}$)* | | *Nutrient Content in Grain (%)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *1999* | | | | *2000* | | | |
| | *1999* | *2000* | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* |
| *Control* | 2.81 | 2.25 | 1.47 | 0.23 | 0.48 | 0.10 | 1.69 | 0.32 | 0.38 | 0.11 |
| *Ash 6* | 2.73 | 2.38 | 1.50 | 0.27 | 0.40 | 0.11 | 1.74 | 0.33 | 0.40 | 0.12 |
| *Ash 12* | 2.64 | 2.12 | 1.50 | 0.26 | 0.39 | 0.13 | 1.56 | 0.34 | 0.40 | 0.12 |
| *Ash 25* | 2.51 | 2.34 | 1.16 | 0.26 | 0.51 | 0.11 | 1.72 | 0.33 | 0.39 | 0.12 |

| | *Dry Matter Production ($t\ ha^{-1}$)* | | *Nutrient Content in Tissue (%)* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | *1999* | | | | *2000* | | | |
| | *1999* | *2000* | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* |
| *Control* | 7.01 | 4.47 | 0.82 | 0.18 | 0.88 | 0.10 | 1.78 | 0.20 | 1.23 | 0.16 |
| *Ash 6* | 7.43 | 5.50 | 1.20 | 0.17 | 0.96 | 0.17 | 1.42 | 0.23 | 1.14 | 0.17 |
| *Ash 12* | 8.46 | 5.78 | 1.01 | 0.19 | 0.94 | 0.19 | 1.25 | 0.25 | 1.08 | 0.14 |
| *Ash 25* | 8.58 | 6.48 | 0.91 | 0.21 | 1.02 | 0.19 | 1.13 | 0.30 | 1.33 | 0.16 |

**Table 32. Removal of N, P, K, and S by 'AC Lacombe' barley seeded in plots containing applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments with and without nitrogen fertilizer.**

| | *Plots With Nitrogen Fertilizer* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *Total Nutrient Removed (kg)* | | | | *% Increase in Removal* | | | |
| | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* |
| *Control* | 542.2 | 82.0 | 327.9 | 37.8 | - | - | - | - |
| *Ash 6* | 630.0 | 83.5 | 419.4 | 70.7 | 16.2% | 1.9% | 27.9% | 86.8% |
| *Ash 12* | 664.1 | 99.5 | 495.6 | 82.6 | 22.5% | 21.4% | 51.1% | 118.5% |
| *Ash 25* | 682.8 | 107.1 | 601.2 | 94.6 | 25.9% | 30.7% | 83.3% | 150.1% |

| | *Plots Without Nitrogen Fertilizer* | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *Total Nutrient Removed (kg)* | | | | *% Increase in Removal* | | | |
| | *N* | *P* | *K* | *S* | *N* | *P* | *K* | *S* |
| *Control* | 216.2 | 35.2 | 138.9 | 19.4 | - | - | - | - |
| *Ash 6* | 249.8 | 41.1 | 154.5 | 27.5 | 15.5% | 16.7% | 11.2% | 42.0% |
| *Ash 12* | 230.2 | 44.1 | 160.9 | 30.1 | 6.5% | 25.3% | 15.9% | 55.4% |
| *Ash 25* | 221.1 | 51.6 | 195.9 | 32.3 | 2.3% | 46.4% | 41.0% | 66.8% |

**Table 33. Probability of F values of 'Harrington' barley grain N, P, K, S, B, Ca, Cu, Fe, Mg, Mn, and Zn nutrient analysis results of for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with and without N – fertilizer.**

| | | *Plots With Nitrogen Fertilizer (1998 – 2000)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *'Harrington'* | *df* | *N* | *P* | *K* | *S* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | *Probability* | | | | | | | | | | |
| *Total* | *35* | | | | | | | | | | | |
| *Rep* | *2* | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | *** | * |
| *Treat* | *3* | n/s | n/s | n/s | **** | * | n/s | n/s | ** | n/s | **** | n/s |
| *Year* | *2* | *** | **** | n/s | n/s | *** | **** | n/s | **** | n/s | n/s | n/s |
| *Treat*Year* | *6* | n/s | n/s | n/s | * | * | n/s | n/s | ** | n/s | *** | n/s |
| *Residual* | *22* | | | | | | | | | | | |

| | | *Plots Without Nitrogen Fertilizer (1999 – 2000)* | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *df* | *N* | *P* | *K* | *S* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | *Probability* | | | | | | | | | | |
| *Total* | *23* | | | | | | | | | | | |
| *Rep* | *2* | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s |
| *Treat* | *3* | n/s | n/s | n/s | * | n/s | * | n/s | n/s | n/s | n/s | n/s |
| *Year* | *1* | **** | *** | n/s | ** | n/s | **** | n/s | * | n/s | n/s | n/s |
| *Treat*Year* | *3* | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s | n/s |
| *Residual* | *14* | | | | | | | | | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

Year also had a significant impact on the nutrient content of 'Harrington' grain samples collected from unfertilized plots. Nitrogen, P, K, and S content of 'Harrington' grain (Table 55) were greater in the last year, while Fe was greater in the second year.

Treatment effect did not have a significant impact on the nutrient content of 'Harrington' grain in plots containing N – fertilizer, but did for samples collected from unfertilized plots. Sulphur and Ca contents of 'Harrington' grain were significantly greater in samples collected from plots amended with 6 and 12.5 t $ha^{-1}$ of wood ash (Table 34).

**Table 34. Average concentration of Ca and S in 'Harrington' barley grain from plots containing applications of 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments without N – fertilizer (1999 - 2000).**

| | *'Harrington' Barley Grain* | |
|---|---|---|
| *Treatment (t $ha^{-1}$)* | *S (% ± SE)* | *Ca (% ± SE)* |
| *Control* | 0.11 ± 0.01b | 0.04 ± 0.01b |
| *Ash 6* | 0.13 ± 0.01a | 0.05 ± 0.00a |
| *Ash 12.5* | 0.13 ± 0.01a | 0.05 ± 0.00a |
| *Ash 25* | 0.12 ± 0.01ab | 0.04 ± 0.00b |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

Treatment-by-year interactions influenced the nutrient content of 'Harrington' grain (Table 33), significantly in plots with N – fertilizer. 'Harrington' barley grain showed increasing B levels during the three years the study was conducted (Table 35). Iron levels of grain samples collected from ash amended trials were significantly lower in 2000 than in 1998 or 1999 (Table 35). Manganese content of the same samples showed significantly lower levels from all ash amended plots than the control in 1998 and 2000. 'Harrington' grain S content (Table 35) was significantly greater in 12.5 and 25 t ha-1 plots in all three years of the study compared to the control.

**Table 35. Average concentration of B, Fe, Mn, and S in 'Harrington' barley grain from plots containing N – fertilizer and applications of 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments (1998 – 2000).**

| | *B (mg $kg^{-1}$ ± SE)* | | |
|---|---|---|---|
| *Treatment (t $ha^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 3.00 ± 0.00b | 5.20 ± 0.89abc | 3.40 ± 0.47bc |
| *Ash 6* | 2.10 ± 0.49c | 8.10 ± 1.70a | 6.53 ± 1.39abc |
| *Ash 12.5* | 3.33 ± 0.33bc | 3.03 ± 0.93bc | 3.73 ± 0.97abc |
| *Ash 25* | 3.67 ± 0.67ab | 6.23 ± 1.12abc | 7.27 ± 1.23ab |

| | *Fe (mg $kg^{-1}$ ± SE)* | | |
|---|---|---|---|
| *Treatment (t $ha^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 54.33 ± 1.20d | 43.00 ± 3.21fg | 34.00 ± 3.00g |
| *Ash 6* | 40.67 ± 3.84fg | 59.33 ± 3.18cd | 37.00 ± 9.50g |
| *Ash 12.5* | 48.67 ± 3.18ef | 70.00 ± 2.08a | 38.67 ± 2.91g |
| *Ash 25* | 55.33 ± 2.67de | 65.67 ± 2.40bc | 39.00 ± 0.58g |

| | *Mn (mg $kg^{-1}$ ± SE)* | | |
|---|---|---|---|
| *Treatment (t $ha^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 12.87 ± 0.15a | 10.43 ± 0.99bc | 13.67 ± 0.72a |
| *Ash 6* | 8.01 ± 0.63e | 10.80 ± 0.92b | 8.50 ± 0.72de |
| *Ash 12.5* | 8.02 ± 0.63e | 10.30 ± 0.61bc | 8.90 ± 1.07de |
| *Ash 25* | 9.33 ± 0.24cde | 9.67 ± 0.84bcd | 8.57 ± 1.16de |

| | *S (% ± SE)* | | |
|---|---|---|---|
| *Treatment (t $ha^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 0.12 ± 0.00d | 0.10 ± 0.01e | 0.10 ± 0.01e |
| *Ash 6* | 0.12 ± 0.01d | 0.13 ± 0.02cd | 0.16 ± 0.00a |
| *Ash 12.5* | 0.14 ± 0.00bc | 0.15 ± 0.00ab | 0.16 ± 0.00a |
| *Ash 25* | 0.14 ± 0.00bc | 0.15 ± 0.01ab | 0.15 ± 0.01ab |

a-g Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (B & S), P=0.01 (Fe), and P=0.001 (Mn) levels; means separated using Fisher's Protected LSD Test

### *4.4.5. Nutrient Uptake – 'Maverick' Canola*

Treatment, year, and treatment-by-year interactions had significant impacts on the nutrient content of 'Maverick' canola oilseed (Table 36). Significant differences in nutrient quality were observed in samples collected from trials with or without the N – fertilizer.

Year had a significant influence on the average nutrient content of 'Maverick' canola seed (Appendix C - Table 56 and Table 57) in samples collected from areas fertilized with N – fertilizer. Nitrogen, B, Cu, and Mn content were significantly greater in 'Maverick' canola oilseed in the second year of the study (Appendix C - Table 56). Levels of K and Zn were significantly greater in the last two years, while Ca was significantly greater in 2000 (Appendix C - Table 56).

Year also had a significant impact on the nutrient content of 'Maverick' canola seed samples collected from unfertilized plots. Copper content of 'Maverick' canola was greater in the second year, while Ca, P, and Zn were greater in the last year of the study (Table 57).

Treatment effect had a significant impact on the nutrient content of 'Maverick' canola (Table 36) in plots containing N – fertilizer. Nitrogen and Zn levels were significantly higher in canola seed in plots containing the 25 t $ha^{-1}$ treatment, while K was significantly lower at all ash rates (Table 37). Boron and Mn showed no significant differences from the control (Table 37), except for the Mn in the 6 t $ha^{-1}$ treatment.

The treatment effect also had a significant influence on the nutrient composition of samples collected from plots without nitrogen fertilizer. The S content of 'Maverick' canola was significantly greater ($P<0.01$) in samples collected from plots amended with 6 (0.43 ± 0.03%) and 12.5 t $ha^{-1}$ (0.45 ± 0.01%) of wood ash than samples from the 25 t $ha^{-1}$ (0.32 ± 0.04%) treatment. No significant differences were observed in S content between any of the ash treatments and the control (0.39 ± 0.02%).

Treatment-by-year interactions influenced the S content of 'Maverick' (Table 36) oilseed, significantly in plots with N – fertilizer. 'Maverick' canola samples (Table 38) collected from plots, containing the N - fertilizer, were significantly greater in the last two years of the study (1999 – 2000), while only the 6 t $ha^{-1}$ ash application was significantly greater in the first year (1998).

**Table 36. Probability of F values of 'Maverick' canola oilseed N, P, K, S, B, Ca, Cu, Fe, Mg, Mn, and Zn nutrient analysis results of for wood ash and control treatments (Treat), N – fertilizer (Fert), year, and their interactions for samples collected from plots with and without N – fertilizer.**

| | | *Plots With Nitrogen Fertilizer (1998 – 2000)* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *'Maverick'* | *df* | *N* | *P* | *K* | *S* | *df* | *B* | *Ca* | *Cu* | *Fe* | *Mg* | *Mn* | *Zn* |
| *Source* | | *Probability* | | | | | *Probability* | | | | | | |
| *Total* | *35* | | | | | *143* | | | | | | | |
| *Rep* | *2* | * | ** | ** | * | *2* | *** | **** | n/s | n/s | ** | n/s | ** |
| *Treat* | *3* | * | n/s | * | **** | *3* | * | n/s | n/s | n/s | n/s | ** | * |
| *Year* | *2* | *** | n/s | *** | ** | *2* | **** | **** | **** | n/s | **** | * | **** |
| *Treat*Year* | *6* | n/s | n/s | n/s | * | *6* | n/s | n/s | n/s | n/s | ** | n/s | n/s |
| *Residual* | *22* | | | | | *130* | | | | | | | |

| | | *Plots Without Nitrogen Fertilizer (1999 – 2000)* | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *df* | *N* | *P* | *K* | *S* | *df* | *B* | Ca | Cu | Fe | Mg | Mn | Zn |
| *Source* | | *Probability* | | | | | *Probability* | | | | | | |
| *Total* | *23* | | | | | *23* | | | | | | | |
| *Rep* | *2* | n/s | n/s | n/s | n/s | *2* | n/s | n/s | n/s | * | n/s | * | * |
| *Treat* | *3* | n/s | n/s | n/s | ** | *3* | n/s | n/s | n/s | n/s | n/s | n/s | n/s |
| *Year* | *1* | n/s | * | n/s | n/s | *1* | n/s | *** | ** | n/s | n/s | n/s | * |
| *Treat*Year* | *3* | n/s | n/s | n/s | n/s | *3* | n/s | n/s | n/s | n/s | * | n/s | n/s |
| *Residual* | *14* | | | | | *14* | | | | | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

**Table 37. Average concentration of N, K, B, Mn, and Zn in 'Maverick canola oilseed from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| *Treatment (t ha$^{-1}$)* | *N* | *K* | *B* | *Mn* | *Zn* |
|---|---|---|---|---|---|
| | ---------------- *(% ± SE)* | ---------------- | ------------------------ | *(mg kg$^{-1}$ ± SE)* | ------------------------ |
| *Control* | 3.09 ± 0.12b | 0.76 ± 0.04a | 13.12 ± 0.56ab | 24.51 ± 0.76b | 37.99 ± 1.25b |
| *Ash 6* | 3.08 ± 0.24b | 0.66 ± 0.04b | 12.45 ± 0.52b | 28.40 ± 0.87a | 40.98 ± 1.29ab |
| *Ash 12.5* | 3.30 ± 0.29ab | 0.69 ± 0.03b | 12.16 ± 0.35b | 25.47 ± 0.74b | 43.41 ± 2.86a |
| *Ash 25* | 3.60 ± 0.15a | 0.69 ± 0.01b | 13.65 ± 0.54a | 26.03 ± 0.48b | 43.18 ± 0.96a |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (N, K, B, & Zn) and P=0.01 (Mn) levels; means separated using Fisher's Protected LSD Test

There were no obvious trends in the Mg content of oilseed samples analyzed over the study period from these treatments (Table 38).

**Table 38. Average concentration of S and Mg over three years in 'Maverick' canola from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| | *S (% ± SE)* | | |
|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 0.31 ± 0.05c | 0.23 ± 0.02d | 0.36 ± 0.02c |
| *Ash 6* | 0.39 ± 0.01b | 0.51 ± 0.02ab | 0.47 ± 0.01a |
| *Ash 12.5* | 0.36 ± 0.01c | 0.50 ± 0.01ab | 0.49 ± 0.02a |
| *Ash 25* | 0.38 ± 0.08bc | 0.52 ± 0.03a | 0.44 ± 0.01b |

| | *Mg (% ± SE)* | | |
|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 0.24 ± 0.00d | 0.28 ± 0.01bc | 0.29 ± 0.01ab |
| *Ash 6* | 0.25 ± 0.00d | 0.29 ± 0.01ab | 0.27 ± 0.01c |
| *Ash 12.5* | 0.25 ± 0.00d | 0.30 ± 0.01a | 0.27 ± 0.01c |
| *Ash 25* | 0.27 ± 0.00c | 0.29 ± 0.00ab | 0.27 ± 0.00c |

a-d Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (S) and P=0.01 (Mg) levels; means separated using Fisher's Protected LSD Test

A significant treatment-by-year interaction (Table 36) among unfertilized plots was observed for the Mg level in 'Maverick' canola oilseed, although there were no obvious trends among the treatments in 1999 or 2000 (Table 39).

**Table 39. Average concentration of Mg in 'Maverick' canola oilseed from plots without N – fertilizer containing applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1999 – 2000).**

| | *'Maverick' Canola Oilseed* | |
|---|---|---|
| *Treatment (t ha$^{-1}$)* | *Mg (% ± SE)* | |
| | *1999* | *2000* |
| *Control* | 0.28 ± 0.01ab | 0.27 ± 0.01abc |
| *Ash 6* | 0.28 ± 0.00ab | 0.26 ± 0.01b |
| *Ash 12.5* | 0.29 ± 0.00 a | 0.27 ± 0.01abc |
| *Ash 25* | 0.25 ± 0.01c | 0.28 ± 0.00ab |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

### *4.4.6. Oilseed Quality*

Oil, protein, glucosinolate, and chlorophyll content within oilseed are all important economic qualities for oilseed producers. Treatment, year, and treatment-by-year interactions had significant impacts on the oil, protein, glucosinolate, and chlorophyll content of the oilseed samples collected in this study (Table 40).

**Table 40. Probability of F values for 'Maverick' canola oilseed quality analysis of samples collected from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| | | *Oil (%)* | *Protein (%)* | *Glucosinolate ($\mu$mol g$^{-1}$)* | *Chlorophyll (mg kg-1)* |
|---|---|---|---|---|---|
| *Source* | *df* | *Probability* | | | |
| *Total* | *71* | | | | |
| *Rep* | *2* | * | * | n/s | n/s |
| *Treat* | *3* | * | **** | **** | n/s |
| *Year* | *2* | **** | **** | **** | **** |
| *Treat*Year* | *6* | * | ** | **** | ** |
| *Residual* | *56* | | | | |

*, **, ***, **** Significant at P=0.05, P=0.01, P=0.001, P=0.0001 respectively; n/s = not significant

There was a significant difference in oil content (Table 41) of samples analyzed from nitrogen – ash amended plots from 1998 to 2000. Oil content (Table 41) was significantly higher in samples collected from ash amended plots in 1998 when compared to the other two years.

Protein content (Table 41) in 1999 was higher than the other two years. Significantly higher chlorophyll content (Table 41) was observed in the last year of the study, compared to the previous two years. Glucosinolate content (Table 41) was higher in nitrogen – ash amended plots in 1999 than in 1998 and 2000. The glucosinolate content of oilseed samples from nitrogen – ash amended plots in 1998 were significantly lower than in the last two years of the study (1999 to 2000).

**Table 41. Average oil, protein, chlorophyll, and glucosinolate content of 'Maverick' canola samples collected from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| *Treatment (t ha$^{-1}$)* | *Oil Content (% ± SE)* | *Protein Content (% ± SE)* | *Chlorophyll Content (mg kg$^{-1}$ ± SE)* | *Glucosinolate Content (μmol g$^{-1}$ ± SE)* |
|---|---|---|---|---|
| *1998* | | | | |
| *Control* | 46.53 ± 1.15b | 20.73 ± 0.49e | 3.82 ± 0.60e | 8.56 ± 0.33f |
| *Ash 6* | 49.17 ± 0.27a | 21.67 ± 0.26d | 3.39 ± 0.80e | 13.77 ± 0.31de |
| *Ash 12.5* | 49.11 ± 0.44a | 21.30 ± 0.40e | 4.51 ± 2.60e | 13.28 ± 0.23e |
| *Ash 25* | 48.77 ± 0.31a | 21.48 ± 0.35de | 2.83 ± 0.24e | 13.42 ± 0.40e |
| *1999* | | | | |
| *Control* | 42.28 ± 0.95e | 22.84 ± 0.45c | 17.95 ± 5.19bcd | 14.28 ± 1.65de |
| *Ash 6* | 43.48 ± 0.27de | 25.91 ± 0.35a | 12.54 ± 2.23d | 23.26 ± 0.75a |
| *Ash 12.5* | 44.45 ± 0.71cd | 24.19 ± 0.36b | 17.00 ± 2.44cd | 20.23 ± 1.02b |
| *Ash 25* | 43.26 ± 0.38e | 26.01 ± 0.43a | 15.36 ± 1.55cd | 24.24 ± 0.39a |
| *2000* | | | | |
| *Control* | 45.24 ± 0.14c | 21.50 ± 0.15de | 25.77 ± 2.09b | 15.06 ± 0.29d |
| *Ash 6* | 44.78 ± 0.22c | 22.87 ± 0.21c | 38.70 ± 4.87a | 17.67 ± 0.55c |
| *Ash 12.5* | 44.63 ± 0.22cd | 23.25 ± 0.18c | 30.27 ± 2.33b | 18.00 ± 0.23c |
| *Ash 25* | 45.19 ± 0.38c | 22.73 ± 0.46c | 19.27 ± 2.88c | 16.89 ± 0.46c |

a-f Means and Standard error (SE) followed by the same letter are not significantly different at P=0.05 (Oil), P=0.01 (Protein & Chlorophyll), and P=0.0001 (Glucosinolate) levels; means separated using Fisher's Protected LSD Test

## 4.5. Discussion

Our results were consistent with those from other studies that found no concerns with elemental uptake by agricultural crops as a result of wood ash applications provided the ash was applied at rates similar to that of agricultural lime (Lerner and Utzinger, 1986; Naylor and Schmidt, 1989; Muse and Mitchell, 1995; Krejsl and Scanlon, 1996; Meyers and Kopecky, 1998).

### *4.5.1. Boron, Cadmium, and Zinc*

This study indicated that wood ash is capable of being a suitable source of nutrients for barley and canola. Boron, Cd, and Zn were of main concern since the presence of these elements at high concentrations in the soil may result in phytotoxic conditions or accumulation within plant, animal, and human tissues. No concerns were found surrounding the uptake of B, Cd, or Zn in any of the grain or plant tissue samples analyzed. Boron and Zn remained within the sufficient ranges according to Alberta Agriculture (1992) while Cd levels in the grain remained below the detection limit of 0.08 mg kg$^{-1}$ even at wood ash applications of 25 t ha$^{-1}$. The Cd analysis of the barley grain and oilseed will become important should the 0.01 mg kg$^{-1}$ limit on grain and oilseed be implemented as indicated by Grant et al (1998). Previous studies by found no significant uptake of Cd by forage tissue at application rates of up to 50 t ha$^{-1}$ (Naylor and Schmidt, 1989; Meyers and Kopecky, 1998), In previous studies elevated B levels were observed in forage crops taken from soils amended with wood ash applications up to 50 t ha$^{-1}$ (Naylor and Schmidt, 1989; Muse and Mitchell, 1995). Our study found that ash treatments did not affect the B in barley tissue. Boron levels increased in 'Harrington' grain but decreased in 'Maverick' canola and 'AC Lacombe' barley grain. Thus uptake may be influenced by crop species. The decrease in B within crop tissues may be related to reduced availability caused by the increase in soil pH which was caused by the application of wood ash (Gupta, 1985). Zinc levels in the plant tissues analyzed in our study were consistent with those found by Naylor and Schmidt (1989), Lickacz et al. (1998), and Meyers and Kopecky (1998).

### *4.5.2. Nutrients*

Studies have shown that wood can serve as a supplemental source of essential nutrients required for plant growth. 'AC Lacombe' barley from plots containing supplemental ash applications removed substantially larger amounts of N, P, K and S than it did in the control treatments. The nutrient content of tissue samples analyzed in this study fell within marginal to sufficient ranges for animal feeds (Alberta Agriculture, 1992) and were consistent with analyses of Alberta Feeds (Alberta Agriculture, 1997). Tissue concentrations of K, Mg, and S in our study were consistent with those found in other studies (Naylor and Schmidt, 1989; Etiegni et al. 1991a; Krejsl and Scanlon, 1996; Meyers and Kopecky, 1998). Erich (1991) suggested that wood ash can be a suitable source of both P and K. An increase in tissue K was found in our study, although tissue P and Mg content levels were often lower than in the control. Magnesium competes with K for uptake by plants that may result in an imbalance between these two elements within the plant tissue (Clapham and Zibilske, 1992). This may help explain our results for Mg and K within the 'AC Lacombe' barley tissue and 'Maverick' oilseed. In 'AC Lacombe' barley Mg within the tissue was lower than the control and K of the same samples was greater; the opposite was observed for 'Maverick' canola.

### *4.5.3. Oilseed Quality*

Oilseed quality, like oil and glucosinolate content, is an important economic factor for oilseed producers. Glucosinolates are secondary metabolites that accumulate within the seed that at high concentrations restrict the use of seed, after oil extraction even if high protein quality is present, for animal feed (McClellan et al 1993; Iqbal et al 1995). Oil and glucosinolate content of canola to some degree are impacted by S fertilization; ash contains up to 1.7% S (Table 2). Increased S fertilization rates can result in increased levels of these two compounds (Nuttal et al 1987). This was observed in our study as increases in S content of the tissue was accompanied by an increase in glucosinolate content of oilseed samples collected from nitrogen – ash treatments during our study. However, the opposite was observed for oil content. Glucosinolate contents for all of the analyzed samples were below the allowable limits under the Canadian definition of 30 $\mu$mol $g^{-1}$ for canola meal for *Brassica* species (McCurdy, 1990).

Chlorophyll content according to Grewal et al. (1998) is influenced by an increase in B and Zn supply and was corroborated by our study. Boron and Zn content of oilseed samples increased in the last two years of the study. Zinc is important in the formation of chlorophyll and many important plant enzymes (Salisbury and Ross, 1992). It was increased as a result of the ash treatments, paralleling the increase in chlorophyll content during the same period. However as oil and chlorophyll content increased between 1999 and 2000, protein and glucosinolate content decreased. The content of oil and protein in oilseed are inversely related; an increase in oil content is associated with a decrease in protein content (Grant and Bailey, 1993).

Climate data (Appendix B) from the study area obtained from Environment Canada indicated that temperature was above the 40-year average for 1998 and 1999 but, below average in 2000, while total precipitation during this time period was less than the 40-year average for all three years. Although changes in oil, protein, glucosinolate, and chlorophyll content were evident in our study, this may have been due to environmental effects as both temperature and moisture affect the traits outlined above. Previous controlled studies indicated that low soil moisture results in low oil content, S fertilization in higher oil content, low temperatures in delayed maturity, high oil content, and low protein. High temperatures increased maturity and protein, while lowering oil content (Daun et al., 1995). These authors also suggested chlorophyll content is affected by environmental stresses such as air temperatures, and moisture conditions explaining the increase observed in our samples possibly due to reduced moisture availability during the study.

### *4.5.4. Future Studies: Wood Ash and Crop Quality*

Producers are constantly faced with increases in costs of fertilizers and regulations surrounding nutrient management strategies. As these two issues gain importance the fertility value of the ash becomes economically important. Until recently, these studies and other research projects have focused on environmental issues related to wood ash applications with very few focusing on the fertility value of the wood ash. As a result, very little information was generated on the availability of the nutrients found within the ash under field conditions. Greenhouse studies have evaluated to a small degree, the availability of some nutrients like P and K. However field studies are required to determine the effective duration that these nutrients are available after single applications of ash. Our field study gave an indication of increased available K and S in the soil after ash applications. These two nutrients were also elevated within seed and tissue samples analyzed. Future field studies should be conducted to ascertain the availability of certain nutrients like P, K, and S or to evaluate wood ash and inorganic fertilizer combinations that would maximize productivity while avoiding nutrient accumulations within the soil profile. For example, many wood ashes are low in Cu. Consequently, ash applications may need to be supplemented with Cu fertilizers.

## 4.6. Conclusion

The application of wood ash at rates of up to 25 t ha$^{-1}$ did not increase the uptake of B, Cd, or Zn by plant tissue. Analysis of grain and oilseed indicated uptake of Cd to be less than 0.08 mg kg$^{-1}$, which would be important should an export limit of 0.1 mg kg$^{-1}$ Cd be placed on grain or oilseed exports. Levels of B and Zn within plant tissue samples were within ranges considered to be marginal to sufficient for these elements in animal feed. Oilseed quality analysis showed glucosinolate levels remained below 30 $\mu$mol $g^{-1}$ even at wood ash application rates up to 25 t $ha^{-1}$.

Concentrations of K, S, B, and Zn were found to be greater in plant tissue samples collected from ash amended soils compared to the control for both barley and canola during the study period (1998 – 2000). These nutrients were also found to be elevated within the soil as result of ash applications. This suggests wood ash used in this study can provide a supplemental source of nutrients in addition to being a potential liming amendment with minimal concerns arising about the uptake of potentially detrimental elements (i.e. B, Cd, and Zn). As a result, applications of wood ash would benefit low pH and nutrient deficient Luvisolic soils, commonly found in the study area.

Under responsible management programs, land application of wood ash can benefit agricultural production and improve the nutrient quality of crops by providing supplemental levels of some important elements.

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# *CHAPTER FIVE: SYNTHESIS*

## 5. SUMMARY AND RECOMMENDATIONS

In studies evaluating the use of wood ash for agricultural production we have come full circle. At one time wood ash was used for the production of potash fertilizer, but the process was labour intensive and was eventually replaced with less expensive K fertilizers (Campbell, 1990). However, increasing production costs for fuel and fertilizer, coupled with low grain prices have directed producers to look for less costly alternatives, such as manure, crop residues, and now wood ash. Studies involving wood ash application to agricultural soils have continued to show applications at agronomic rates (<50 t $ha^{-1}$) have increased soil pH and available nutrients resulting in increased dry matter production, grain yield, and improved crop quality. The present field study, and earlier studies, have indicated that low rates of 12.5 t $ha^{-1}$ may provide as much benefit as higher ash applications (>12.5 Mg $ha^{-1}$) during the short term (i.e. <3 years). Naylor and Schmidt (1989) suggested that higher applications might provide a longer effect. However, this field study on wood ash could not support or negate this contention. Single applications of agricultural lime have shown long term effects (Alberta Agriculture, 1996) some up to 30 years after the initial application (Beckie and Ukrainetz, 1996). Extensive studies in the field and greenhouse have been conducted in Europe and the United States. However, little information was available about the effects that wood ash applications would have on Canadian soils.

The objectives of this study were to determine the suitable application rates for agricultural soils. This was accomplished by evaluating the effect wood ash applications would have on soil chemical properties, crop growth, and crop nutrient quality. Results could then be applied to other research projects or used for recommendations for commercial applications. The field study was conducted on a Gray Luvisolic soil, 50 km north east of Athabasca, AB. Treatments included four rates of wood ash (0, 6, 12.5, and 25 t $ha^{-1}$) with and without nitrogen fertilizer (46-0-0) and three vegetation treatments involving a canola and two barley cultivars. Total precipitation during the study period (1998 to 2000) was found to be 32, 15, and 24% lower than the long term average in 1998, 1999, and 2000, respectively. Soil and plant samples were collected over a three-year period (1998 to 2000) for chemical analysis and for determining dry matter production, grain and oilseed yield. The following sections summarize the results obtained in these series of studies. Since the study was conducted on one site with only two crops, conclusions should be limited to the soil and crops used for this study.

### 5.1. Effect on Soil Quality and Crop Production

#### *5.1.1. Soils*

The liming capability of wood ash has been well documented in the literature. Applications of wood ash at 6 to 25 t $ha^{-1}$ increased the pH of Gray Luvisolic soils used in this study from moderately acidic (pH~5.5) to near neutral (pH=6.6 to 7) levels in this area. Only a slight increase in pH was observed between the 12.5 and 25 t $ha^{-1}$ application rates, probably due to the soils buffering capacity. Wood ash applications had no significant effect on soil salinity at the above application rates. At no time during the study did soil pH, EC, $B_{HWS}$, Cd, and total Zn levels exceed upper limits set under the Alberta Tier – 1 Guidelines for Contaminated Sites. Ash applications increased available levels of K, S, B, and Zn within the soil, while ash treatments decreased the availability of Fe within the soil. This study confirmed earlier observations that applications of wood ash might provide a suitable source for these nutrients for plant growth.

### *5.1.2. Biomass and Yield*

Ash applications significantly increased barley dry matter and grain production and oilseed yield in canola; these increases were higher in combination with N – fertilizer. Production may have also been influenced by the dry weather experienced during the study, as total precipitation was 32, 15, and 24% lower than the 40-year average for the Athabasca area. No significant differences for yield and dry matter production were observed in the last two years of the study among treatments containing only ash. On average, there appeared to be no significant benefit to seed yield or dry matter production in applying 12.5 versus 25 t ha$^{-1}$ except for the dry matter production of 'AC Lacombe' barley. There was no detrimental effect observed in the productivity of barley or canola as a result of wood ash applications up to 25 t ha$^{-1}$.

### *5.1.3. Crop Quality*

No significant concerns were observed over the uptake of B, Cd, or Zn by barley or canola during the study. Boron and Zn were within marginal to sufficient ranges for feed, while Cd levels, for barley and canola, remained below the detection limit, of 0.08 mg kg$^{-1}$ and 1.0 mg kg$^{-1}$. Cadmium levels in the 25 t ha$^{-1}$ treatments with and without N – fertilizer remained below the detection limit of 0.08 mg kg$^{-1}$ during the study. This would be significant if upper limits of 0.1 mg Cd kg$^{-1}$ are placed on grain and oilseed to be traded on international markets.

Nutrient content within the plant tissue was within marginal to sufficient ranges for feed. Significant increases in K, S, and Zn uptake were observed in analyzed plant samples these same elements were also elevated within the soil samples collected during the study. This was also observed in earlier studies indicating that wood ash is a suitable source of these nutrients.

Applications of wood ash affected the protein and glucosinolate content of oilseed samples collected during the study. However, glucosinolate content remained below the Canadian definition for canola meal (30 μmol $g^{-1}$) (McCurdy, 1990). Protein content of oilseed samples was higher in plots treated with wood ash.

### *5.1.4. Application Rates*

Wood ash application rates used in this study were considered to be equivalent to agricultural lime rates used for commercial agricultural production. Significant increases in soil pH, nutrient availability, dry matter production, grain and oilseed yield were obtained through applications of 12.5 and 25 t $ha^{-1}$. However, on average the difference between these two rates was often not significant. This suggests that 12.5 t $ha^{-1}$ application rate is the most beneficial when considering both production increases, and crop quality. Increases in nutrient uptake were often not significantly different between 12.5 and 25 t $ha^{-1}$ application rates. On the other hand, if decreases in nutrient levels were observed they were often smaller at 12.5 t $ha^{-1}$ than at 25 t $ha^{-1}$. Higher applications of ash may have a long - term effect (>3 years) on increasing productivity. The present three-year study could not substantiate this and so longer term field studies are required to shed light on this important aspect of wood ash disposal.

## 5.2. Wood Ash as an Alternative to Agricultural Lime

In Alberta, there are roughly 2.5 million hectares of strongly acidic and 11.1 million hectares of moderately acidic soils that are farmed annually (Alberta Agriculture, 1996). A large portion of these soils lies within the Peace River and Central Regions of Alberta. A freight assistance program was available to offset the cost of transporting lime from quarry to farm, up until the early 1990's when the program was terminated (Lickacz, Personal communication). The termination of the freight assistance program has resulted in the use of lime for agricultural production in many areas of Central Alberta becoming cost prohibitive. Therefore high pH waste by – products such as wood ash and waste lime have the potential to replace Agricultural Lime for increasing soil pH. Mills that produce waste lime or operate cogeneration facilities are capable of supplying this market.

There are approximately 16 different operations in Alberta that operate cogeneration facilities, involving the burning of biomass to produce energy for utilization in the production process. These facilities include Lumber mills, Kraft pulp mills, Oriented Strand Board (OSB) plants, and independent cogeneration plants that generate nearly 110, 000 tonnes of wood ash, that could be land applied, on an annual basis. There are approximately 2.5 million hectares of strongly acidic and 11 million hectares of moderately acidic soils in Alberta. A majority of these lie in the Central and Peace River Region of Alberta (Alberta Agriculture, 1996). The Central and Peace River Region of Alberta are the primary regions where cogeneration facilities producing wood ash are located. As a result, land area should never factor in limiting the application of wood ash.

Luvisolic soils can range from moderately to strongly acidic. Results from the present study and other previously documented studies have shown wood ash to be a suitable alternative for liming. Alberta Agriculture studies suggested lime requirements of these soils to be in the order of 2.5 to 5 tonnes per hectare, to raise the soil pH one unit. It is estimated to cost nearly \$5000 to haul and spread 1 load (40 t: \$125 $t^{-1}$) of agricultural lime in the study area. Alberta Agriculture (1996) suggested that the lime requirement to raise the soil pH from 5 to 6 in Luvisolic soils where the present study was conducted would be about 5 t $ha^{-1}$. The average $CaCO_3$ equivalence of the wood ash used in this study was around 50%; therefore 2 tonnes of ash should accomplish the same pH increase as 1 tonne of agricultural lime. For example, if the lime requirement based on values from Alberta Agriculture (1996), of a specific site were 5 t $ha^{-1}$ this would require and application of 10 t $ha^{-1}$ of wood ash to accomplish the same increase. Therefore, the transportation and application of wood ash in this area would have an equivalent value of \$62 per tonne compared to \$125 per tonne of agricultural lime, based on its use as a liming amendment in this area of Alberta. In addition to the liming ability of wood ash it also contains many essential macronutrients and micronutrients essential for plant growth, including P, K, and S that could aid in agricultural production.

### 5.3. Wood Ash as a Nutrient Supplement

Chemical analysis of the ash used in this study was found to have 1.4, 4.0 and 1.7% of total-P (as $P_2O_5$), total-K (as $K_2O$) and total-S respectively. So 10 t $ha^{-1}$ of wood ash would add 140-kg $ha^{-1}$ as $P_2O_5$, 400-kg $ha^{-1}$ as $K_2O$, and 170-kg $ha^{-1}$ of S in addition to increasing soil pH. Based on cost estimates obtained for $P_2O_5$ (\$400 $tonne^{-1}$), $K_2O$ (\$210 $tonne^{-1}$), and S (\$400 $tonne^{-1}$) fertilizers, this would give the ash a fertilizer value of nearly \$20 $tonne^{-1}$.

Studies have shown increased levels of various nutrients in crop tissues as a result of ash applications when compared to untreated controls and limed controls. Meyers and Kopecky (1998) showed that levels of nutrients within crop tissue from ash amended soils were similar to tissue levels of samples collected from limed and fertilized controls. Previous studies on wood ash applications have observed increases in P, K, and S within plant tissue and elevated levels of available forms of these nutrients within the soil. Our study found elevated levels of P, S and other trace elements in the plant tissue along with increased availability in the soil as a result of ash applications. Our data also showed a substantial increase in removal of P, K, and S by 'AC Lacombe' barley collected from plots containing wood ash applications of 6 to 25 t $ha^{-1}$. Based on our results, and results from previous studies the addition of wood ash would provide supplemental levels of P, K, and S that might reduce the requirement initially by the end user for P-K-S fertilizer applications. However a better understanding of the availability of these nutrients within the ash needs to be acquired before these recommendations can be applied.

### 5.4. Marketability of Wood Ash

Various factors should be considered when developing land application programs involving wood ash. These include the following questions:

1. **What are the characteristics of the wood ash being proposed for land application?**

Chemical characteristics of wood ashes used in this study and others in the literature are variable (Table 2). However, studies have shown at rates considered to be agronomically acceptable ($<50$ t $ha^{-1}$), applications of wood ash posed no environmental concerns.

2. **What are the characteristics of the surrounding agricultural or forest soils and would they be suitable for wood ash applications?**

In Alberta, the Central and Peace River Regions contain the majority of acid soils (Alberta Agriculture, 1996); thus they are the primary regions where wood ash applications would occur. These two regions of Alberta are where companies, operating cogeneration facilities, interested in land application programs are mainly located. Should lab analysis of initial soil samples indicate high pH, EC, or SAR these soils would be unsuitable for ash applications.

3. **What are the short and long – term environmental consequences of wood ash applications?**

Wood ash research has shown ash applications to increase soil pH, while also increasing agricultural productivity. Many of these research projects have lasted less than 3 years. Longer studies involving wood ash application are required to determine the length of time before second applications could be applied. In addition, none of the studies conducted to date have involved multiple wood ash applications and most of the studies have involved single high rate applications. Although, higher applications are necessary to determine rates at which toxicity symptoms may occur the effects on soil chemistry and crop production resulting from multiple applications needs to be understood.

**4. Are there current guidelines pertaining to the application of wood ash to agricultural soils?**

At the time of this study there were no guidelines pertaining to wood ash application in the Province of Alberta. Applications were regulated under CCME and Alberta Tier – 1 Guidelines for Contaminated Sites. Since the initiation of this project, Alberta Environment in association with mills, from the Forest Industry in Alberta, that generate wood ash have since developed a draft set of guidelines to regulate the application of wood ash generated by these facilities.

**5. What are the alternatives to wood ash? Is there a cheaper alternative to wood ash that provides similar benefits?**

When used as a liming agent, wood ash can only compare to marl or agricultural lime. Marl is a water deposited material consisting of clay, sand, and calcium carbonate allowing it to be used effectively as a source of lime (Agriculture Canada, 1982). Agricultural lime consists mainly of dolomitic or calcitic limestone. Calcitic limestone contains <5% magnesium carbonate, while dolomitic limestone contains levels >5% (Agriculture Canada, 1982). Although the $CaCO_3$ equivalence of wood ash is lower than agricultural lime, wood ash contains many nutrients and trace elements that agricultural lime lacks (Table 2). As a result, significant levels of P-K-S are applied as a result of achieving the same increase in soil pH by applying wood ash instead of agricultural lime. Wood ash as an alternative liming amendment could have an average value of

$75 per tonne delivered and spread. In addition, the end user also benefits from supplemental nutrient additions of P, K, S, and other essential for plant growth valued at nearly $20 tonnes$^{-1}$. As a result wood ash may have a value up to $100 per tonne as a liming alternative and nutrient supplement; making it less costly than Agricultural Lime while providing extra benefits.

### 6. Who would benefit economically from the application of wood ash?

Economically, both generators and end users of wood ash benefit from its use. Generators landfill less wood ash extending the use of existing landfills, reducing the associated costs of hauling, maintenance, and new landfill construction. End users benefit by obtaining a soil amendment that would improve soil chemical and physical properties resulting in increased crop production in the form of higher grain yields, and increased dry matter production.

### 7. Who benefits environmentally from the land application of wood ash?

Agricultural, industrial, and community partners would all benefit environmentally from the land application of wood ash. Management practices involving the land application of wood ash can provide benefits to all parties. Less land would be required for landfill construction, less waste is being landfilled, nutrients are being recycled back into the system from which they originated, and increases in agricultural productivity would be obtained.

8. **Would the farmers and local communities accept and support the land application of wood ash?**

Local producers surrounding the mill (Al – Pac) producing the ash used in the present study are supportive of wood ash land application as an alternative management practice. Many realize the environmental and economic benefits that can be obtained from the reuse of this product.

### 5.5. Recommendations for Further Research

A large majority of studies conducted on wood ash application have observed increases in crop productivity as a result of ash applications. These also addressed environmental aspects associated with nutrient and metal uptake by plant tissues. Applications of ash up to 25 t ha$^{-1}$ continued to show increase benefits to agricultural productivity. Many greenhouse studies on wood ash application have indicated that the ash can provide moderate levels of macro- and micronutrients, in addition to some essential trace elements. Based on our results the following is a list of recommendations for future wood ash studies:

1. Applications rates for future studies should focus around 10 to 15 t ha$^{-1}$.
2. Evaluate the effect of ash applications on other cereal, oilseed, and forage crops. Determine the availability of P, K, S and other trace elements within the ash under field conditions; information would be extremely beneficial for ash applications as this may aid in reducing extra fertilizer costs.
3. Studies should monitor the availability of heavy metals within ash amended soils as pH begins to decrease.
4. Projects should be conducted over periods longer than 5 years to allow for multiple ash applications to be incorporated into the study.

5. Determination of the optimal times for application by comparing spring versus fall applications.
6. Evaluate the effect of top dressing versus incorporation after ash applications.
7. Feed quality of forage and silage crops grown on ash amended soils.

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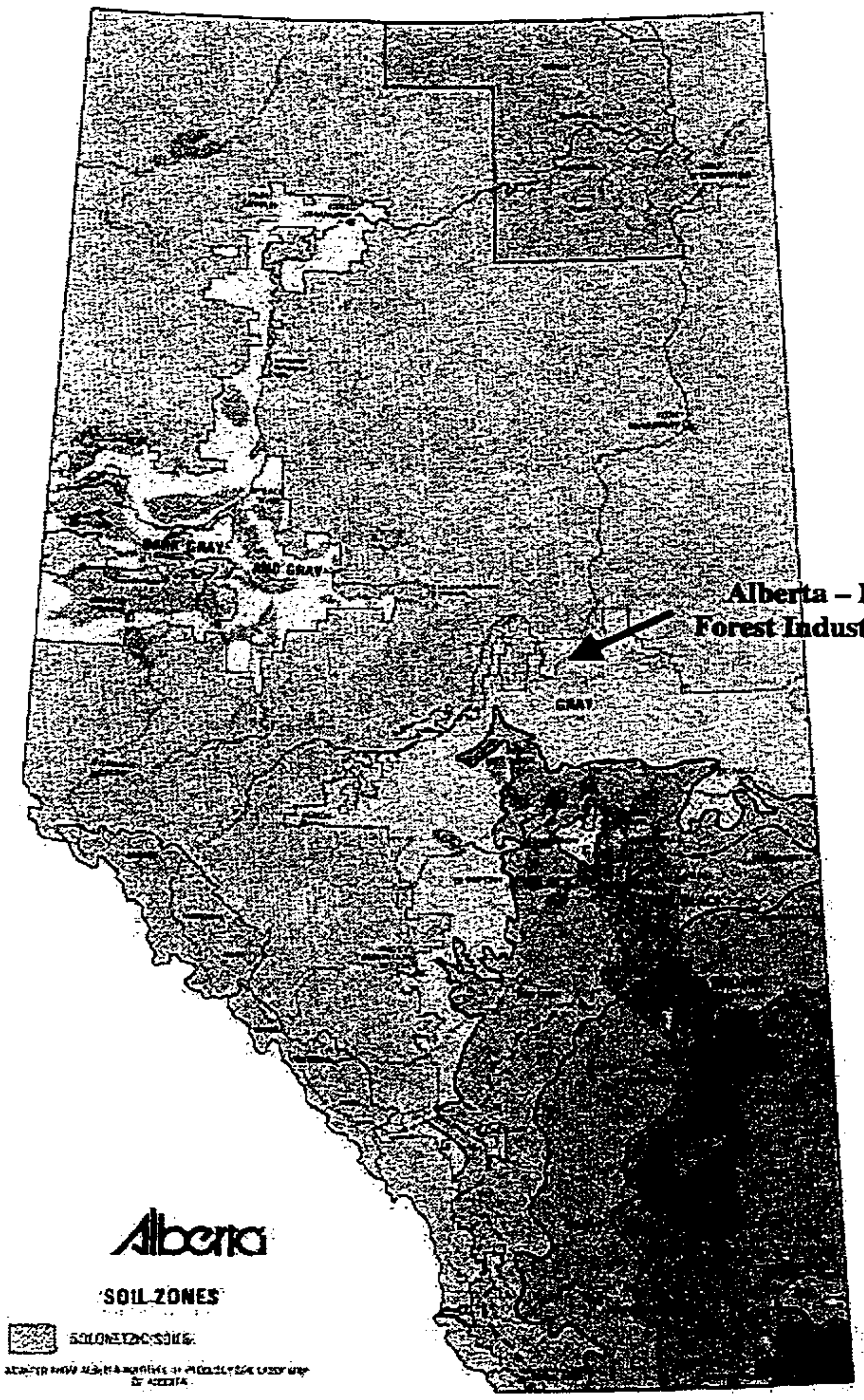
Meyers, N.L., and Kopecky, M.J. 1998. Industrial wood ash as a soil amendment for crop production. TAPPI Journal. 81 (4): 123-130.

# *APPENDICES*

## Appendix A

## Field Trial Location & Layout (1998 – 1999)



Alberta – Pacific Forest Industries, Inc.

**Figure 6. Field study location in the Luvisolic soil zone in central Alberta (Soil Zone Map is adapted from FS541-1 Alberta Fertilizer Guide with permission of Alberta Agriculture, Food and Rural Development).**

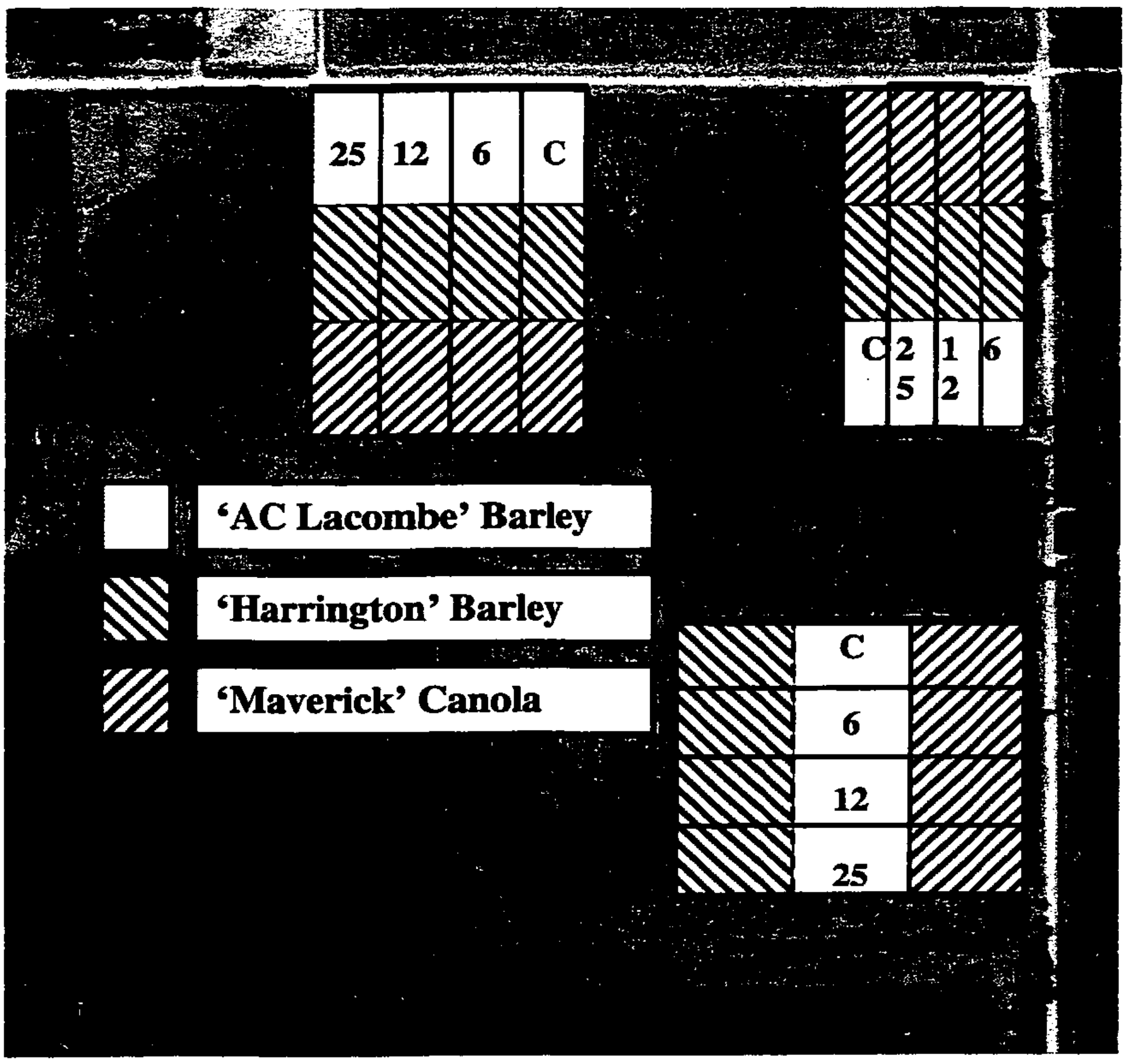


**Figure 7. Field layout for this study including treatment (6, 12.5 (12),and 25 t ha$^{-1}$ wood ash and control (C)) and crop locations from 1998 to 2000 (Aerial photo reprinted with the permission of Air Photo Services, Alberta Environment).**

## Appendix B

## Climate Data (1998 – 2000)

**Table 42. Average monthly and total annual precipitation received in the study area period from 1998 to 2000, including the 40-year average.**

| | Total | | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *40-Yr Average* | 503.1 | - | 26.1 | 21.2 | 20.0 | 24.2 | 47.4 | 87.3 | 96.9 | 66.6 | 42.6 | 22.9 | 23.2 | 24.6 |
| *1998* | 342.4 | -31.9% | 24.0 | 2.0 | 10.0 | 11.5 | 29.0 | 77.9 | 64.9 | 25.1 | 38.9 | 17.6 | 15.5 | 26.0 |
| *1999* | 426.2 | -15.3% | 58.5 | 35.0 | 4.0 | 26.9 | 34.4 | 96.2 | 49.0 | 52.0 | 35.2 | 8.0 | 10.0 | 17.0 |
| *2000* | 381.9 | -24.1% | 12.0 | 11.0 | 14.0 | 19.2 | 67.6 | 97.1 | 105.0 | 56.0 | | | | |

**Table 43. Average monthly temperature in the study area period from 1998 to 2000, including the 40-year average.**

| | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *40-Yr Average* | -16.0 | -11.1 | -5.2 | 3.9 | 10.3 | 14.2 | 16.2 | 15.2 | 10.3 | 5.2 | -4.8 | -11.9 |
| *1998* | -18.9 | -5.7 | -4.9 | 6.2 | 13.0 | 14.2 | 16.7 | 16.8 | 10.1 | 4.5 | -6.9 | -14.4 |
| *1999* | -16.4 | -10.9 | -3.7 | 5.3 | 9.2 | 13.8 | 15.2 | 17.6 | 10.2 | 5.3 | -3.7 | -5.5 |
| *2000* | -15.5 | -8.6 | -2.6 | 4.3 | 8.4 | 13.4 | 16.9 | 15.3 | | | | |

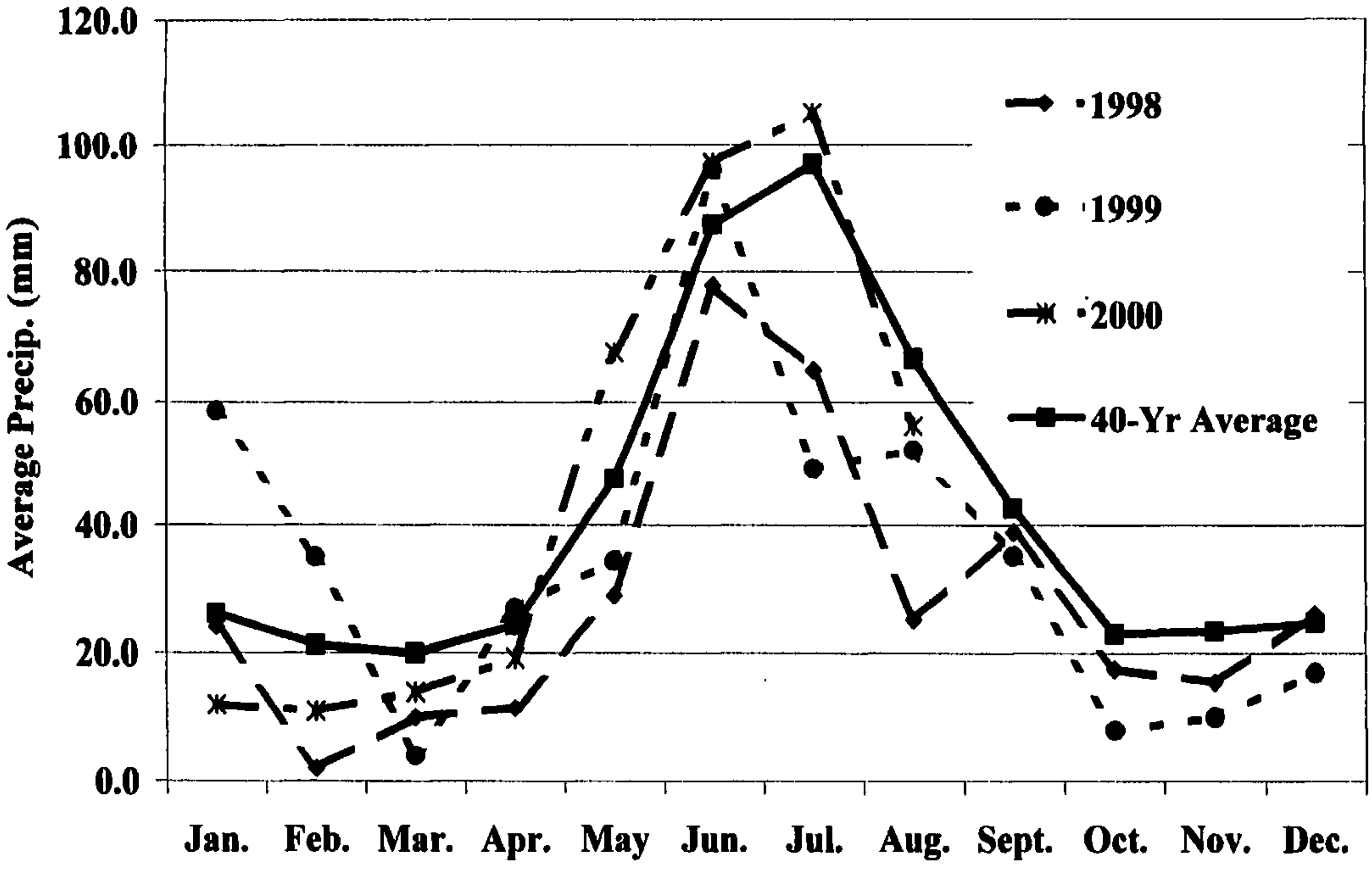


**Figure 8. Average monthly precipitation in the Athabasca region from 1998 – 2000 including the 40-yr average.**

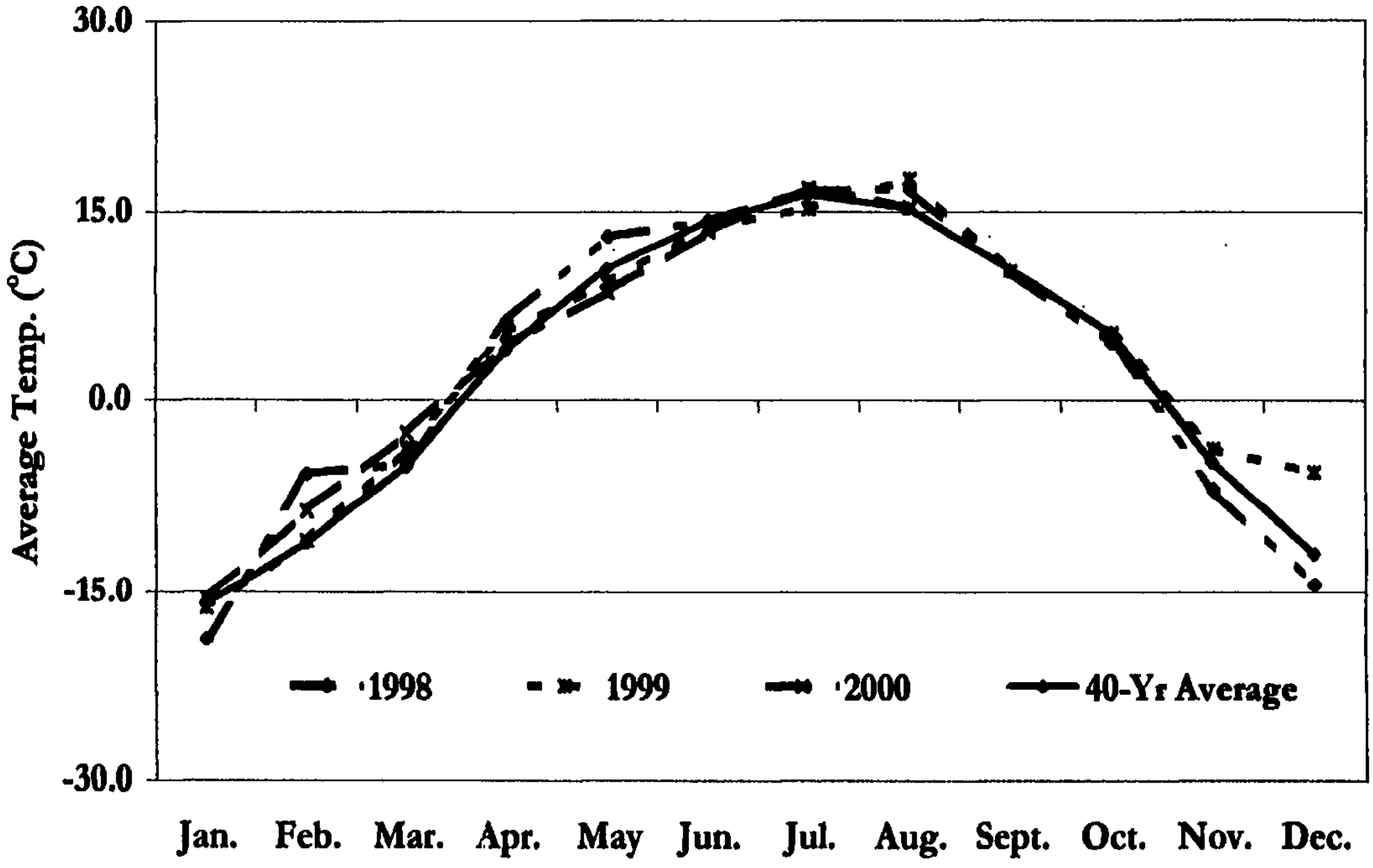


**Figure 9. Average monthly temperature in the Athabasca Region from 1998 – 2000 including the 40-yr average.**

## Appendix C

## Data for Figures in Text

**Table 44. Soil pH in 1:2 soil-0.01M $CaCl_2$ saturated pastes for soil samples taken in May and October from 6, 12.5, and 25 t $ha^{-1}$ wood ash and control treatments (1998 to 2000).**

| | *Soil pH: 0.01 M $CaCl_2$ (pH ± SE)* | | | | | |
|---|---|---|---|---|---|---|
| *Treatment (t $ha^{-1}$)* | *1998* | | *1999* | | *2000* | |
| | *May* | *October* | *May* | *October* | *May* | *October* |
| *# Of Days From Wood Ash Incorporation* | *-17* | *+135* | *+348* | *+500* | *+714* | *+866* |
| *Control* | 5.5 ± 0.04bC | 6.1 ± 0.08cA | 6.0 ± 0.05dA | 5.8 ± 0.06dB | 5.8 ± 0.05dB | 5.8 ± 0.05dB |
| *Ash 6* | 5.5 ± 0.07bD | 6.8 ± 0.08bB | 6.7 ± 0.07cB | 6.9 ± 0.05cA | 6.8 ± 0.04cB | 6.5 ± 0.04cC |
| *Ash 12.5* | 5.9 ± 0.06aD | 6.9 ± 0.05aAB | 6.9 ± 0.06bBC | 7.0 ± 0.04bcAB | 7.0 ± 0.03bAB | 6.8 ± 0.04bC |
| *Ash 25* | 5.7 ± 0.01aC | 7.0 ± 0.07aB | 7.1 ± 0.05aAB | 7.2 ± 0.04aA | 7.2 ± 0.02aA | 7.0 ± 0.04aB |

a-m Means and Standard error (SE) followed by the same letter (A-D: within row; a-d: within column) are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

-/+: (-) Indicates the number of days before wood ash was incorporated, (+) indicates the number of days after incorporation.

**Table 45. Average nutrient concentrations of P, S, B, Fe, and Mn in soil samples collected from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000).**

| | *kg ha$^{-1}$ ± SE* | | | | |
|---|---|---|---|---|---|
| | *P* | *S* | *B* | *Fe* | *Mn* |
| *May 1998* | 71.68 ± 7.36a | 29.80 ± 4.06b | 1.72 ± 0.09bc | 136.38 ± 11.75a | 66.13 ± 12.33a |
| *October 1998* | 56.59 ± 7.27b | 59.31 ± 11.13a | 2.08 ± 0.06a | 105.27 ± 9.23b | 8.11 ± 0.92b |
| *May 1999* | 48.07 ± 3.56b | 29.26 ± 3.34b | 2.01 ± 0.10a | 130.50 ± 8.77a | 10.92 ± 0.87b |
| *October 1999* | 32.89 ± 3.00c | 62.86 ± 19.54a | 1.84 ± 0.07b | 82.46 ± 5.17c | 6.53 ± 0.56b |
| *May 2000* | 34.02 ± 4.25c | 27.77 ± 2.72b | 1.63 ± 0.08c | 86.01 ± 7.33c | 6.53 ± 0.66b |
| *October 2000* | 30.89 ± 3.91c | 32.67 ± 3.47b | 1.73 ± 0.08bc | 113.26 ± 7.96b | 7.61 ± 0.64b |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 46. *H. vulgare* L. cv. 'AC Lacombe' barley dry matter yield, data shown is the average yield of whole plant samples taken from plots containing applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments with and without N – fertilizer (1999 & 2000) (data for Figure 2).**

| | *Dry Matter Yield (t ha$^{-1}$ ± S.E)* | |
|---|---|---|
| *Treatment (t ha$^{-1}$)* | *Without N – Fertilizer* | *With N - Fertilizer* |
| *Control* | 5.74 ± 0.25f | 7.61 ± 0.23d |
| *Ash 6* | 6.46 ± 0.24e | 9.69 ± 0.22c |
| *Ash 12.5* | 7.12 ± 0.27d | 10.64 ± 0.23b |
| *Ash 25* | 7.53 ± 0.23d | 11.39 ± 0.23a |

a-f Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 47. Dry matter yield results *H. vulgare* L. cv. 'AC Lacombe', data shown are averages of 0.25-m$^2$ whole plant samples taken from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000) (data for Figure 3).**

| | *Dry Matter Yield ± SE (t ha$^{-1}$)* | | |
|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 6.17 ± 0.27e | 7.55 ± 0.28d | 7.68 ± 0.36d |
| *Ash 6* | 7.61 ± 0.37d | 9.68 ± 0.27c | 9.70 ± 0.36c |
| *Ash 12.5* | 8.15 ± 0.39d | 10.84 ± 0.34b | 10.43 ± 0.33bc |
| *Ash 25* | 10.59 ± 0.39b | 11.86 ± 0.36a | 10.91 ± 0.26b |

a-e Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 48. *H. vulgare* L. cv. 'AC Lacombe' (1999 & 2000) data shown are average yield from a 9-m$^2$ area harvested from plots containing applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments with and without N – fertilizer (data for Figure 4).**

| | *Grain Yield (t ha$^{-1}$ ± SE)* | |
|---|---|---|
| *Treatment (t ha$^{-1}$)* | *Without N – Fertilizer* | *With N - Fertilizer* |
| *Control* | 2.53 ± 0.15c | 3.64 ± 0.17b |
| *Ash 6* | 2.55 ± 0.13c | 3.63 ± 0.15b |
| *Ash 12.5* | 2.38 ± 0.13c | 4.05 ± 0.16a |
| *Ash 25* | 2.43 ± 0.11c | 4.35 ± 0.13a |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 49. Grain yield for *H. vulgare* L. cv. 'AC Lacombe', results shown are the averages of 9-m$^2$ samples taken from plots containing N – fertilizer and applications of 6, 12.5, and 25 t ha$^{-1}$ wood ash and control treatments (1998 – 2000) (data for Figure 5).**

| | *'AC Lacombe' Grain Yield ± SE (t ha$^{-1}$)* | | |
|---|---|---|---|
| *Treatment (t ha$^{-1}$)* | *1998* | *1999* | *2000* |
| *Control* | 3.38 ± 0.23e | 3.60 ± 0.18e | 3.68 ± 0.32e |
| *Ash 6* | 4.69 ± 0.15ab | 3.48 ± 0.19e | 3.79 ± 0.24de |
| *Ash 12.5* | 5.06 ± 0.18a | 3.86 ± 0.23cd | 4.23 ± 0.23bcd |
| *Ash 25* | 4.71 ± 0.17ab | 4.34 ± 0.19bc | 4.36 ± 0.19b |

a-e Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 50. Average concentrations of N, P, K, S, Ca, and Mg of 'AC Lacombe' barley tissue in plots with N – fertilizer (1998 – 2000).**

| | ------------------------------------------------------------ (% ± SE) | | | | | ------------------------------------------------------------ | ($mg\ kg^{-1}$ ± SE) |
|---|---|---|---|---|---|---|---|
| *Year* | *N* | *P* | *K* | *S* | *Ca* | *Mg* | *B* |
| *1998* | 1.32 ± 0.04b | 0.25 ± 0.01a | 1.56 ± 0.05a | 0.23 ± 0.01a | 0.44 ± 0.01a | 0.12 ± 0.00a | 5.44 ± 0.23a |
| *1999* | 1.31 ±0.03b | 0.16 ± 0.01c | 1.24 ± 0.04b | 0.17 ± 0.01b | 0.38 ± 0.01b | 0.13 ± 0.00a | 4.61 ± 0.16b |
| *2000* | 1.73 ± 0.04a | 0.22 ± 0.01b | 1.55 ± 0.04a | 0.18 ± 0.01b | 0.46 ± 0.01a | 0.10 ± 0.00b | 3.71 ± 0.27c |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 51. Average concentrations of P, B, Fe, Mn, and Zn of 'AC Lacombe' barley grain in plots with N – fertilizer (1998 – 2000).**

| | *(% ± SE)* | | *(mg kg$^{-1}$ ± SE)* | | |
|---|---|---|---|---|---|
| *Year* | *P* | *B* | *Fe* | *Mn* | *Zn* |
| *1998* | 0.28 ± 0.01b | 3.20 ± 0.08b | 52.87 ± 1.29b | 12.28 ± 0.37a | 34.30 ± 0.73b |
| *1999* | 0.22 ± 0.01b | 5.82 ± 0.39a | 58.43 ± 1.70a | 10.44 ± 0.32c | 37.27 ± 0.91a |
| *2000* | 0.35 ± 0.04a | 3.39 ± 0.41b | 40 98± 2.29c | 11.63 ± 0.31b | 34.00 ± 0.70b |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 52. Average concentrations of N, P, K, Mg, Al, B, Cu, and Mn of 'AC Lacombe' barley tissue in plots without N – fertilizer (1999 & 2000).**

| | % ± SE | | | | $mg\ kg^{-1}$ ± SE | | |
|---|---|---|---|---|---|---|---|
| *Year* | *N* | *P* | *K* | *Mg* | *B* | *Cu* | *Mn* |
| *1999* | 0.99 ± 0.07b | 0.18 ± 0.01b | 0.95 ± 0.04b | 0.13 ± 0.00a | 5.06 ± 0.45a | 2.97 ± 0.09b | 8.66 ± 0.70b |
| *2000* | 1.39 ± 0.10a | 0.24 ± 0.02a | 1.19 ± 0.06a | 0.11 ± 0.00b | 3.17 ± 0.45b | 3.83 ± 0.28a | 11.90 ± 1.36a |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 53. Average concentrations of N, P, Ca, Mg, B and Fe of 'AC Lacombe' grain in plots without N – fertilizer (1999 & 2000).**

| | % ± SE | | | | mg kg$^{-1}$ ± SE | |
|---|---|---|---|---|---|---|
| *Year* | *N* | *P* | *Ca* | *Mg* | *B* | *Fe* |
| *1999* | 1.41 ± 0.09b | 0.26 ± 0.02b | 0.04 ± 0.00b | 0.11 ± 0.00a | 8.34 ± 1.69a | 54.41 ± 3.68a |
| *2000* | 1.68 ± 0.05a | 0.33 ± 0.01a | 0.05 ± 0.00a | 0.10 ± 0.00b | 3.77 ± 0.52b | 34.33 ± 1.98b |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 54. Average concentrations of N, P, and Ca of 'Harrington' barley grain in plots treated with N – fertilizer (1998 – 2000).**

| | (% ± SE) | | |
|---|---|---|---|
| *Year* | *N* | *P* | *Ca* |
| *1998* | 2.00 ± 0.10b | 0.29 ± 0.01b | 0.05 ± 0.00a |
| *1999* | 2.01 ± 0.09b | 0.25 ± 0.01c | 0.04 ± 0.00b |
| *2000* | 2.45 ± 0.05a | 0.35 ± 0.01a | 0.05 ± 0.00a |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 55. Average concentrations of N, P, S, Ca, Al and Fe of 'Harrington' grain in plots without N – fertilizer (1999 & 2000).**

| | % ± SE | | | | mg kg$^{-1}$ ± SE |
|---|---|---|---|---|---|
| *Year* | *N* | *P* | *S* | *Ca* | *Fe* |
| *1999* | 1.41 ± 0.04b | 0.30 ± 0.01b | 0.11 ± 0.00b | 0.04 ± 0.00b | 46.41 ± 2.89a |
| *2000* | 2.09 ± 0.12a | 0.37 ± 0.01a | 0.13 ± 0.01a | 0.05 ± 0.00a | 36.58 ± 3.43b |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 56. Average concentrations of N, P, K, B, Ca, Cu, Mn, and Zn of 'Maverick' canola oilseed in plots treated with N – fertilizer (1998 – 2000).**

| | % ± SE | | | $mg\ kg^{-1} \pm SE$ | | | |
|---|---|---|---|---|---|---|---|
| *Year* | *N* | *K* | *Ca* | *B* | *Cu* | *Mn* | *Zn* |
| *1998* | 2.79 ± 0.18c | 0.63 ± 0.02b | 0.47 ± 0.00b | 11.50 ± 0.24b | 3.27 ± 0.05b | 25.05 ± 0.47b | 35.66 ± 0.52b |
| *1999* | 3.74 ± 0.17a | 0.72 ± 0.02a | 0.45 ± 0.01b | 14.96 ± 0.53a | 3.95 ± 0.10a | 27.52 ± 0.93a | 40.34 ± 1.33a |
| *2000* | 3.28 ± 0.07b | 0.75 ± 0.04a | 0.59 ± 0.01a | 12.08 ± 0.31b | 2.77 ± 0.05c | 25.74 ± 0.40b | 41.17 ± 1.86a |

a-c Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

**Table 57. Average nutrient levels of P, Ca, and Cu in 'Maverick' oilseed in plots without N – fertilizer (1999 & 2000).**

| | % ± SE | | $mg\ kg^{-1} \pm SE$ | |
|---|---|---|---|---|
| *Year* | *P* | *Ca* | *Cu* | *Zn* |
| *1999* | 0.68 ± 0.02b | 0.47 ± 0.02b | 3.48 ± 0.15a | 38.00 ± 1.76b |
| *2000* | 0.76 ± 0.02a | 0.61 ± 0.02a | 2.74 ± 0.10b | 43.68 ± 1.70a |

a-b Means and Standard error (SE) followed by the same letter are not significantly different at the P=0.05 level; means separated using Fisher's Protected LSD Test

## Appendix D

### Characterization of Wood Ash Used in This Study

*Wood Ash Physical Characteristics*

**Table 58. Physical characteristics of the wood ash used in this field study, results shown are maximum, minimum, and average values for analyses conducted on the wood ash since 1996.**

| | *Bulk Density ($t/m^3$)* | *Ash %* | *Total Carbon %* | *C/N* | *Conductivity ($dS\ m^{-1}$)* | *pH (0.01 M $CaCl_2$)* | *CaCO3 Equiv. (%)* |
|---|---|---|---|---|---|---|---|
| *Alberta Tier 1 Criteria* | | | | | 2.0 | 6 - 8.5 | |
| *Alberta Municipal Biosolids* | | | | | | | |
| *CCME - Agricultural Limits* | | | | | | | |
| *Wood Ash* | | | | | | | |
| *Maximum* | 0.88 | 99.3 | 13.5 | 450 | 70 | 13.7 | 78.7 |
| *Minimum* | 0.35 | 76.4 | 3.3 | 195 | 28.8 | 12.5 | 7.5 |
| *Average* | 0.48 | 92.1 | 7.6 | 324.3 | 50.3 | 13.1 | 52 |
| *s.d.* | 0.19 | 7.2 | 3.8 | 99.3 | 14.1 | 0.4 | 26.8 |
| *SE* | 0.07 | 2.2 | 1.4 | 40.5 | 5 | 0.1 | 9.5 |
| *# of Samples Analyzed* | 7 | 11 | 7 | 6 | 8 | 13 | 8 |

*Wood Ash Available Nutrients*

**Table 59. Concentration of available nutrients contained in the wood ash used in this field study, results shown are maximum, minimum, and average values for analyses conducted on the wood ash since 1996; also shown are calculated nutrient loadings based on average concentrations and application rates used in this study.**

| | $NO_3$-N | $NH_3$-N | P | $P_2O_5$ | Cu | Fe | Mn | Zn | B | Al | Ca | Mg | Na | K | $K_2O$ | $SO_4$-S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ppm | | | | | | | | | | % | | | | | |
| *Alberta Tier 1 Criteria* | | | | | | | | | 2.0 | | | | | | | |
| *Alberta Municipal Biosolids* | | | | | | | | | 10.0 | | | | | | | |
| *CCME -Agricultural Limits* | | | | | | | | | 2.0 | | | | | | | |
| *Wood Ash* | | | | | | | | | | | | | | | | |
| *Maximum* | 59 | 10 | 10 | 23.0 | 1.8 | 40.4 | 1.5 | 11.1 | 27.0 | 5 | 14.2 | 0.1 | 0.5 | 5.8 | 7 | 1.1 |
| *Minimum* | 19 | 1.4 | 1 | 3.7 | 0.5 | 1 | 0.1 | 0.5 | 2.6 | 1 | 1.3 | 0 | 0.2 | 2.6 | 3.1 | 0.4 |
| *Average* | 38.3 | 6.3 | 4.7 | 10.8 | 0.7 | 1.1 | 0.5 | 2.1 | 15.8 | 1.8 | 8.6 | 0.1 | 0.3 | 3.8 | 4.5 | 0.7 |
| *s.d.* | 13.9 | 3.1 | 3.2 | 7.3 | 0.5 | 14.8 | 0.5 | 4.7 | 9.1 | 1.8 | 4.6 | 0 | 0.1 | 1 | 1.2 | 0.3 |
| *SE* | 5.3 | 1.2 | 1.2 | 3 | 0.2 | 5.6 | 0.2 | 1.8 | 3.4 | 0.8 | 1.9 | 0 | 0 | 0.4 | 0.5 | 0.1 |
| *# of Samples Analyzed* | 7 | 7 | 7 | 6 | 7 | 7 | 7 | 7 | 7 | 5 | 6 | 6 | 6 | 7 | 7 | 7 |

*Nutrients or Metals Applied with Each Treatment (kg ha$^{-1}$): Based on average wood ash concentration.*

| *Treatment (t ha$^{-1}$)* | $NO_3$-N | $NH_3$-N | P | $P_2O_5$ | Cu | Fe | Mn | Zn | B | Al | Ca | Mg | Na | K | $K_2O$ | $SO_4$-S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *6* | 0.23 | 0.04 | 0.03 | 0.06 | 0 | 0.01 | 0 | 0.01 | 0.09 | 0.01 | 516 | 3.4 | 18 | 226 | 271 | 40 |
| *12.5* | 0.48 | 0.08 | 0.06 | 0.13 | 0.01 | 0.01 | 0.01 | 0.03 | 0.2 | 0.02 | 1074 | 7 | 38 | 471 | 565 | 83 |
| *25* | 0.96 | 0.16 | 0.12 | 0.27 | 0.02 | 0.03 | 0.01 | 0.05 | 0.4 | 0.05 | 2149 | 14.1 | 75 | 942 | 1131 | 166 |

*Wood Ash Total Nutrients*

**Table 60. Concentration of total nutrients contained in the wood ash used in this field study, results shown are maximum, minimum, and average values for analyses conducted on the wood ash since 1996; also shown are calculated nutrient loadings based on average concentrations and application rates used in this study.**

| | *N* | *P* | *$P_2O_5$* | *Ca* | *Mg* | *Na* | *K* | *$K_2O$* | *S* | *Cu* | *Fe* | *Mn* | *Zn* | *B* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | | | | | | | | | ppm | | | | |
| *Alberta Tier 1 Criteria* | | | | | | | | | *500* | *80* | | | *120* | |
| *Alberta Municipal Biosolids* | | | | | | | | | | *200* | | | *300* | |
| *CCME -Agricultural Limits* | | | | | | | | | | *150* | | | *600* | |

| *Wood Ash* | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Maximum* | 0.03 | 0.9 | 2.2 | 31 | 4 | 15 | 6.3 | 7.6 | 3.9 | 180 | 11000 | 1200 | 3300 | 230 |
| *Minimum* | 0.01 | 0.1 | 0.1 | 10 | 1.1 | 0.2 | 0.3 | 0.4 | 0.1 | 3 | 10 | 5.6 | 86 | 12 |
| *Average* | 0.03 | 0.6 | 1.4 | 21.1 | 1.9 | 1.6 | 3.3 | 4 | 1.7 | 53.3 | 4272.3 | 597.2 | 1504 | 121.3 |
| *s.d.* | 0.01 | 0.2 | 0.5 | 5.7 | 0.6 | 3.5 | 1.5 | 1.8 | 1 | 40.9 | 3450.8 | 269.8 | 918 | 61.1 |
| *SE* | 0 | 0 | 0.1 | 0.9 | 0.1 | 0.5 | 0.2 | 0.3 | 0.2 | 6.3 | 538.9 | 42.1 | 141.7 | 9.7 |
| *# of Samples Analyzed* | 7 | 41 | 41 | 42 | 42 | 42 | 42 | 42 | 34 | 42 | 41 | 41 | 42 | 40 |

*Nutrients or Metals Applied with Each Treatment (kg $ha^{-1}$): Based on average wood ash concentration.*

| *Treatment (t $ha^{-1}$)* | *N* | *P* | *$P_2O_5$* | *Ca* | *Mg* | *Na* | *K* | *$K_2O$* | *S* | *Cu* | *Fe* | *Mn* | *Zn* | *B* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *6* | 1.5 | 36 | 82 | 1265 | 116 | 94 | 198 | 237 | 102 | 0.3 | 26 | 3.6 | 9 | 0.7 |
| *12.5* | 3.1 | 74 | 171 | 2636 | 242 | 196 | 412 | 494 | 213 | 0.7 | 53 | 7.5 | 19 | 1.5 |
| *25* | 6.3 | 148 | 341 | 5271 | 483 | 393 | 824 | 989 | 426 | 1.3 | 107 | 15 | 38 | 3 |

*Wood Ash Total Metals*

**Table 61. Concentration of total metals contained in the wood ash used in this field study, results shown are maximum, minimum, and average values for analyses conducted on the wood ash since 1996; also shown are calculated metal loadings based on average concentrations and application rates used in this study.**

| | *Al* | *Ba* | *Cd* | *Co* | *Cr* | *Pb* | *Hg* | *Mo* | *Ni* | *Se* | *Ag* | *Sr* | *Sn* | *Ti* | *V* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *%* | *ppm* | | | | | | | | | | | | | |
| *Alberta Tier 1 Criteria* | | *600* | *1.0* | *20* | *100* | *50* | *0.20* | *4* | *40* | *2* | | | | | *100* |
| *Alberta Municipal Biosolids* | | | *1.5* | | *100* | *100* | *0.50* | | *25* | | | | | | |
| *CCME -Agricultural Limits* | | *750* | *3.0* | *40* | *750* | *375* | *0.80* | *5* | *150* | *2* | *20* | | *5* | | *200* |

| *Wood Ash* | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Maximum* | 2.1 | 1730 | 28 | 11 | 34 | 14 | 0 | 4 | 32 | <10 | <1 | 1051 | 7 | 560 | 29 |
| *Minimum* | 0.0 | 40 | 0.4 | 2.5 | 7 | 1 | 0 | 1 | 6 | 0.6 | <0.5 | 240 | 5 | 10 | 3 |
| *Average* | 0.7 | 703.3 | 11.7 | 6.9 | 43.4 | 36.1 | 0.2 | 2.5 | 17 | 2 | 0.8 | 597.1 | 5.7 | 243.3 | 25.4 |
| *s.d.* | 0.6 | 449.5 | 6.2 | 1.7 | 7.4 | 4.6 | 0 | 0.8 | 5.9 | | | 216.7 | 1.4 | 162.5 | 7 |
| *SE* | 0.1 | 74.9 | 1.1 | 0.3 | 1.4 | 1.1 | 0 | 0.2 | 1 | | | 38.9 | 1 | 28.3 | 1.7 |
| *# of Samples Analyzed* | 41.0 | 36 | 35 | 29 | 30 | 17 | 4 | 25 | 36 | 1 | 1 | 31 | 2 | 33 | 18 |

*Nutrients or Metals Applied with Each Treatment (kg ha$^{-1}$): Based on average wood ash concentration.*

| *Treatment (t ha$^{-1}$)* | *Al* | *Ba* | *Cd* | *Co* | *Cr* | *Pb* | *Hg* | *Mo* | *Ni* | *Se* | *Ag* | *Sr* | *Sn* | *Ti* | *V* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *6* | 44 | 4.2 | 0.07 | 0.04 | 0.3 | 0.22 | 0 | 0.02 | 0.10 | 0.01 | 0 | 3.6 | 0.03 | 1.5 | 0.15 |
| *12.5* | 92 | 8.8 | 0.15 | 0.09 | 0.5 | 0.45 | 0 | 0.03 | 0.21 | 0.03 | 0.01 | 7.5 | 0.07 | 3 | 0.32 |
| *25* | 184 | 17.6 | 0.29 | 0.17 | 1.1 | 0.90 | 0.01 | 0.06 | 0.42 | 0.05 | 0.02 | 15 | 0.14 | 6.1 | 0.64 |

## Appendix E

## Photos of Spreading Equipment

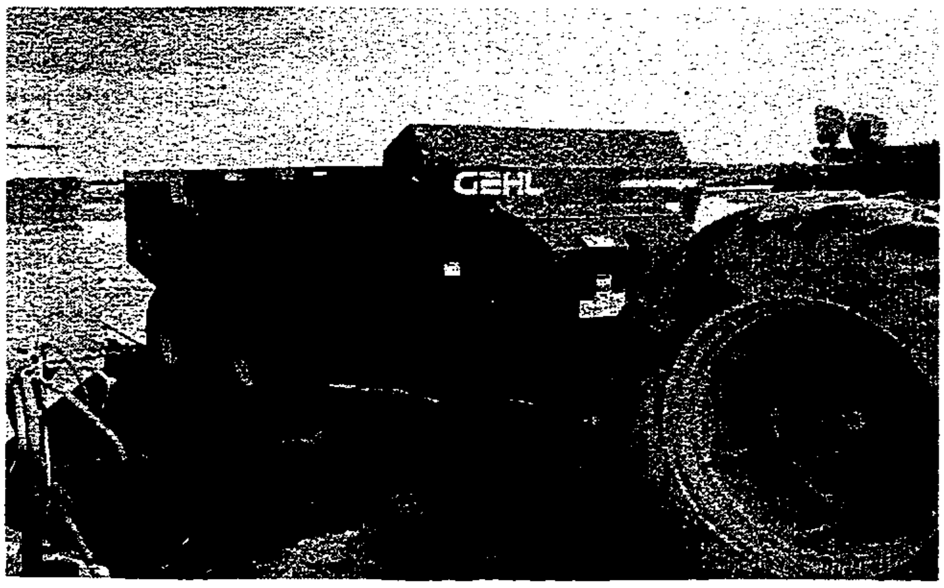


**Figure 10. GEHL Scavenger side discharge manure spreader used for wood ash application in the field study.**

**Figure 11. Application of wood ash using the side discharge manure spreader.**

# Appendix F

## Crop Photos Taken from Nitrogen – Ash Plots (1998 – 2000)

**Figure 12a.**

**Figure 12b.**

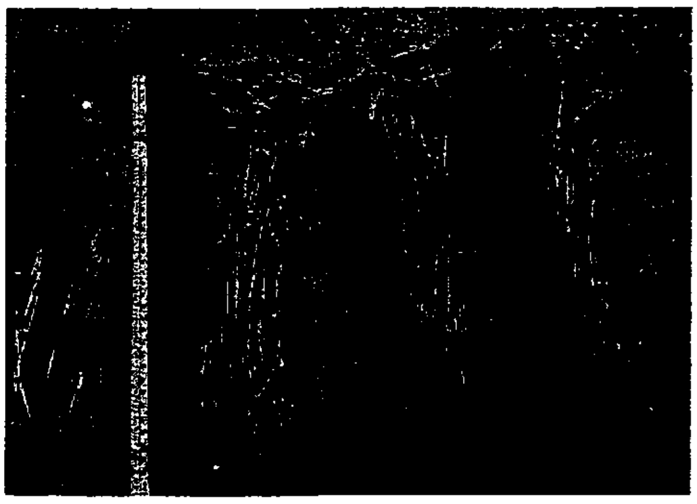


**Figure 12c.**

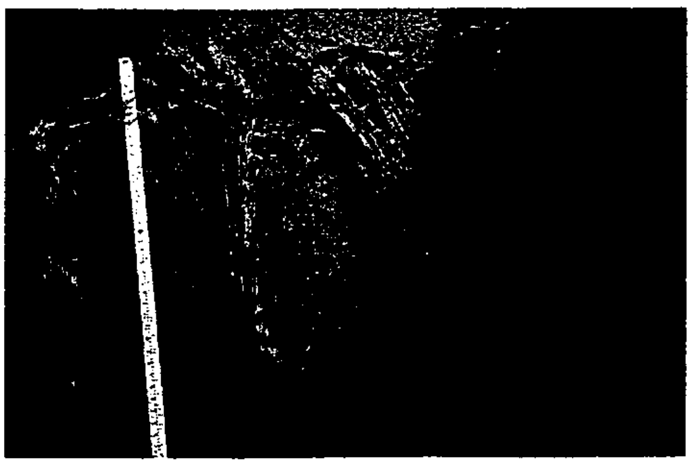


**Figure 12. Figure 12a-c show whole plant samples of 'AC Lacombe' barley taken from nitrogen – ash amended plots in 1998 (Figure 12a), 1999 (Figure 12b), and 2000 (Figure 12c). Samples were taken from (Left to Right): Control; Ash 6 t/ha; Ash 12.5 t/ha; Ash 25 t $ha^{-1}$.**

Figure 13a.

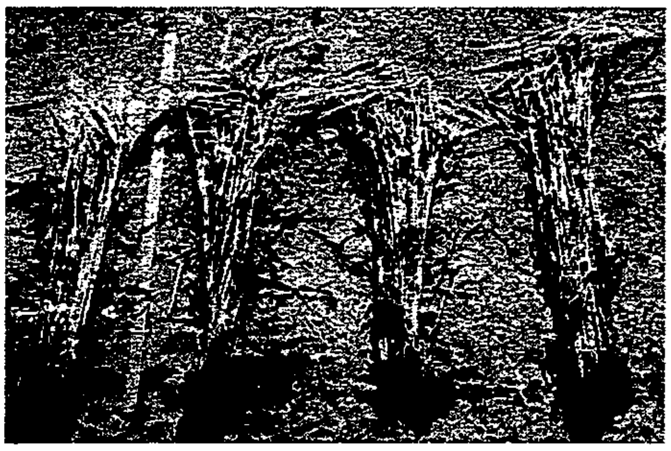


Figure 13b.

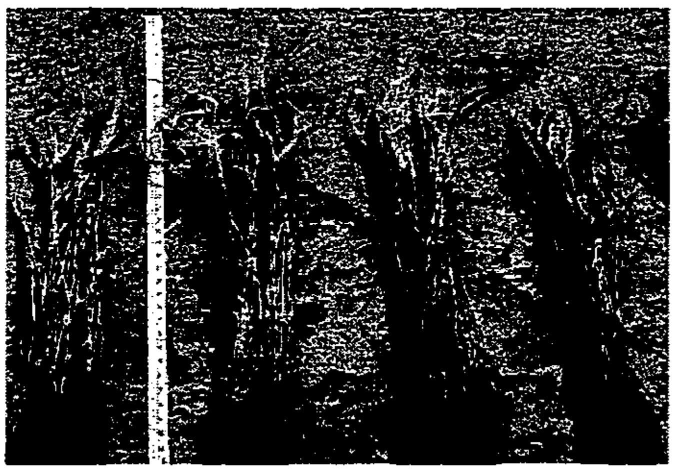


Figure 13c.

**Figure 13. Figure 13a-c show whole plant samples of 'Harrington' barley taken from nitrogen – ash amended plots in 1998 (Figure 13a), 1999 (Figure 13b), and 2000 (Figure 13c). Samples were taken from (Left to Right): Control; Ash 6 t/ha; Ash 12.5 t/ha; Ash 25 t ha$^{-1}$.**

**Figure 14a.**

**Figure 14b.**

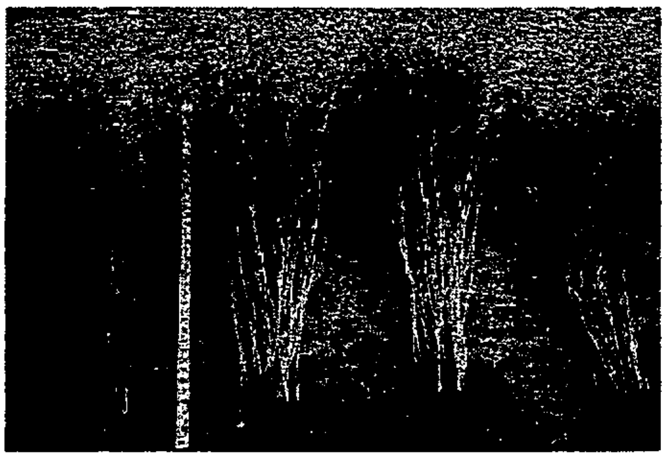


**Figure 14c.**

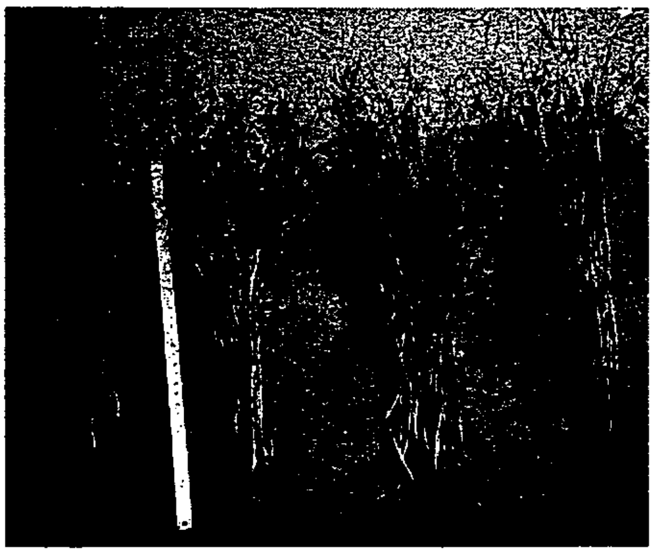


**Figure 14. Figures 14a-c show whole plant samples of 'Maverick' canola taken from nitrogen – ash amended plots in 1998 (Figure 14a), 1999 (Figure 14b), and 2000 (Figure 14c). Samples were taken from (Left to Right): Control; Ash 6 t/ha; Ash 12.5 t/ha; Ash 25 t ha$^{-1}$.**