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Wood Ash Improved Soil Properties and Crop Yield for Nine Years and Saved Fertilizer

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Abstract

Wood ash may be used to mitigate soil acidity and improve crop production. We compared effects of wood ash and recommended fertilizers on soil properties of a Gray Luivsol, crop yields and contribution margins in southeast Peace, Alberta, Canada. The CHK (no fertilizer, inoculation or wood ash), FRT (recommended fertilizers or inoculation), ASH (wood ash rate to supply amounts of phosphorus equivalent to the FRT treatment); and ASH+N (same as ASH + N fertilizer or inoculation) treatments were applied in 2006 and 2007. Their effects were studied from 2006 to 2014. Wood ash had all the essential plant nutrients, except nitrogen. Soil samples collected in 2007, 2008 and 2013 had or tended to have higher pH, P, K, Ca, Ca:Mg ratio, S, Cu, Zn and B levels for the ASH and ASH+N treatments than the CHK and FRT treatments. In the 2006 and 2007, the seed yields were ASH+N > FRT > ASH > CHK. The seed yields in 2008, 2010, 2012, 2013 and 2014 were greater from both the wood ash treatments than other treatments. Extra contribution margin from the ASH+N over the FRT treatment was \$751/ha, i.e. \$97 Mg^{-1} of applied wood ash. Overall, wood ash reduced fertilizer expenditure and improved seed yield, contribution margin and soil properties, with residual effects observed up to seven years and likely for few more years.

Keywords: acidic Luvisol, crop yield, contribution margin, fertilizer, northwest Alberta, nutrients, soil properties, wood ash

1. Introduction

In northwestern Canada, Gray acid soils occur most frequently in the higher precipitation areas with tree cover as dominant vegetation and Luvisolic soils; and about 2.55 million ha have a top soil pH of 6.0 or less and another 3.44 million ha have pH 6.1 to 6.5 (Lickacz, 2002). Applications of lime on these soils have increased yields of barley, canola, and field pea by 19 to 37% in northwestern Canada (Nyborg & Hoyt, 1978; Arshad & Gill, 1996; Arshad, Gill, Turkington, & Woods, 1997; Arshad, Franzluebbers, & Gill, 1999). However, the use of agricultural lime is constrained by its high cost, mainly due to transportation charges.

On acid soils, plant growth and crop yields are reduced by factors such as Al, Mn or Fe toxicity; Ca, P, N, or Mo deficiency; higher root diseases incidence, and slower organic matter breakdown and nutrient cycling by the micro flora (Marschner, 1991; Edmeades & Ridley, 2003; Arshad et al., 1997). In western Canada, forage yield was higher with wood ash than with lime plus P fertilizer (Lickacz, 2002); lime and wood ash increased microbial biomass and C mineralization, and changed the functional structure of bacterial communities (Lupwayi, Arshad, Azooz, & Soon, 2009); and the increases were wood ash = lime for soil pH, and wood ash > lime for the available P, aggregation of soil and yield of barley, canola and field pea (Arshad, Soon, Azooz, Lupwayi, & Chang, 2012). Greater increase in crop yield with wood ash compared with lime in these studies was attributed to a more rapid change in soil pH, and increased P availability. Beneficial effects of 25 Mg ha^{-1} wood ash supplemented by N fertilizer were observed on barley biomass and seed yield (Patterson, Acharya, Thomas, Bertschi, & Rothwell, 2004a) and canola seed yield (Patterson, Acharya, Bertschi, & Thomas, 2004b) in central Alberta. In an incubation study in central Canada, wood ash increased the pH, Ca, Mg, K and P of a Brunisol and a Luvisol, but had little effect on their microbial activity and biomass (Pugliese et al., 2014). In a review, Demeyer, Nkana, and Verloo (2001) attributed the plant growth benefits on wood ash-amended soils to increases in the availability of P, Ca, Mg, K, and B, and decreases in Al and Mn toxicity. Wood ash application on land has been extensively used in northern Europe to curtail the cost of landfills and to improve forest productivity (Vance, 199; Demeyer et al., 2001; Pitman, 2006). The preceding studies show that wood ash is an appropriate amendment for acidic soils, to improve soil properties and increase crop yields. However, these studies have not investigated long term residual effects and fertilizer savings from wood ash use.

In Alberta, about 170 Gg of wood ash was produced in 2001 from 18 forest products facilities (Alberta Environment, 2002), and most wood ash-generating mills are located in northwestern Alberta where most of the acid soils also occur. However, the composition of wood ash depends on its source and is highly variable because the chemical properties of wood ash depend primarily on the types of wood and combustion system used. For example, Lickacz (2002) stated that the range of percent calcium carbonate equivalent (%CCE) of wood ash is generally 55 to 65 with some facilities up to 100%. Wood ash used by Erich & Ohno (1992) contained 12.1 g kg^{-1} total P, 18 g kg^{-1} total K, and 10.7 g kg^{-1} total Mg; and wood ash used by Arshad et al. (2012) had 0.26 g NO_3-N kg^{-1} and 0.93 g P kg^{-1}. A review by Vance (1996) showed a wide range of macronutrient (P, K, Ca, Mg, N) and micronutrient (Mn, Cu, Zn, B, Mo) concentrations in wood ash from different sources; e.g., the P concentration in 24 samples ranged from 0.3 to 14.4 g P kg^{-1} with a median value of 4.2 g P kg^{-1}.

In earlier studies, residual effects were observed on crop yield for 2 to 3 years from wood ash and for much longer period from lime; and little research has been documented on the contribution of nutrients in wood ash towards fertilizer savings and crop production. The objectives of present study were to compare the effects of recommended fertilizer, wood ash and wood ash plus N fertilizer applications to an acidic soil on soil properties, crop production and contribution margins during the application years, and to investigate the residual effects of treatments for a long-term assessment.

2. Materials and Methods

Previous wood ash samples from Tolko Industries Ltd., High Prairie, Alberta were found to contain all the essential plant nutrients, except N, with the total neutralizing value ranging from 79 to 108% (average about 90%) and effective neutralizing value ranging from 41 to 96% (average about 71%), and was considered to be a good source of several essential plant nutrients (S.J. Patterson, personal communication). Thus wood ash from Tolko Industries, High Prairie, Alberta, Canada was collected and used for the present study.

The bulk density and water retention of wood ash were determined in triplicate, using 1-L containers. The chemical properties were determined using EPA 3050 method, concentrated nitric and hydrochloric acids plus hydrogen peroxide as extractants (Environmental Protection Agency, Revision 2., 1996; Environmental Protection Agency Revision 3., 2007).

The field experiment was conducted near Falher (NW16-77-21-W5; lat. 55.674 N, long. 117.208 W), Alberta, Canada. The soil is a silty clay Gray Luvisol, referred as Boralf in USDA Soil Taxonomy and Albic / Gleyed Luvisol in FAO - WRB (Soil Classification Working Group, 1998; Luvkulich & Arocena, 2011). The spring soil moisture and rain data during the growing seasons were collected from the Ballater weather station located 4 km south of the experimental site (Table 1).

Table 1. Spring soil moisture (SSM) and monthly rainfall in different years (mm). Data collected from the Ballater weather station located four km south of the study site

Time	2006	2007	2008	2010	2012	2013	2014	Normal^z
SSM	173	183	139	87	101	184	89	130
May	114	85	37	66	50	20	21	46
June	91	67	36	18	91	102	58	81
July	94	20	24	20	77	65	30	76
Aug.	46	63	37	54	77	14	3	57
Total	519	418	273	245	396	385	201	390

Note. ^{z}Thirty-year average.

The following 4 treatments were applied in 2006 and 2007:

1) *CHK*: Check without fertilizer, inoculation or wood ash;

2) *FRT*: Soil test based fertilizer rates. In 2006, all FRT plots received 15 kg P ha^{-1}, canola (*Brassica napus* L.) and barley (*Hordeum vulgare* L.) plots received 83 kg N ha^{-1}, canola plots also received 25 kg S ha^{-1}, and the field pea (*Pisum sativum* L.) seeds were inoculated with *Rhizobium leguminosarum bv. vicea*. In 2007, all plots received 78 kg N ha^{-1}, 19 kg P ha^{-1}and 12 kg S ha^{-1}.

3) *ASH*: Received 3.36 and 4.37 Mg ha^{-1} wood ash in 2006 and 2007, respectively; to supply equivalent amounts of P as in the FRT treatment, based on approximate available P (4.4 g P kg^{-1}) in wood ash;

4) *ASH+N*: Same as ASH plus N fertilizer or inoculation of peas mentioned in the FRT treatment.

Three sets of the treatment plots were laid out adjacent to each other to study the treatment effects on different crops in similar soil. These 3 sets of plots were termed as the North, Centre and South sites. At each site, randomized complete block design (RCBD) with four replications was used, and the test plots were 2 m wide and 8 m long.

In 2006, wood ash as well as N and S fertilizers were spread on the soil surface of the designated plots, followed by rotor tillage (working depth of 10 cm) on all plots, and seeding with canola (North), peas (Centre) and barley (South) with seed row placed P fertiliser and inoculant. In 2007, wood ash application on the soil surface was followed by rotor tillage (working depth of 10 cm) and oat (*Avena sativa* L.) grown on all plots; and when applied the P fertilizer was seed row placed and N and S fertilizers were side banded.

From 2008 to 2014, crops were grown using similar agronomic practices and fertilizer rates on all plots; and these data represents the residual effects of wood ash and fertilizer applications in 2006 and 2007. Wheat (*Triticum aestivum* L.) was grown in 2008 and 2010. Field pea, flax (*Linum usitatissimum* L.) and canola were seeded in 2009. Plots were managed as chem-fallow in 2011, due to flooding. Oat, wheat and barley were seeded in 2012. Canola was grown in 2013 and 2014. No data were collected from North site in 2006, North and Centre sites in 2008, from all sites in 2009, and from Centre and South sites in 2012; due to unevenness of crop growth resulting from factors that were not related to the treatments (i.e., excess water and herbicide drift).

Soil samples were collected from the 0-15 and 15-30 cm soil depths. The May 2006 samples, collected before the application of treatments, were composite from the whole experimental area. The May 2007 (Table 3) and October 2008 (Table 4) soil samples for each treatment were composites of 36 cores, 3 cores from 4 replications in each of the North, Centre and South sites. In October 2013, separate soil samples were collected for each site, and were composites of 4 cores for each plot (Table 5). The May 2007 samples represent the effects of only one wood ash application in 2006 while the October 2008 and 2013 samples represent the effects of two (2006 and 2007) wood ash applications. Analytical methods used were loss on ignition for organic matter; water extraction for pH; Mehlich No. 3, followed by analyses using ICP-OES for P, K, Mg, Ca, Na, Fe, Cu, Zn, B, and Mn (Soil and Plant Analysis Council, 1999). Nitrate-N was determined using 0.01 M K_2SO_4 extraction and extract analysed colorimetrically (American Public Health Association, American Water Works Association, and Water Environment Association, 2012). The data on soil properties and available forms of nutrients in soil (Tables 3, 4, and 5) are presented to show the changes due to the treatments relative to the CHK.

Data for each site-year were subjected to analyses of variance, using the ARM software (Gylling Data Management Inc., 2015) for the following statistical model.

Y {ij} = Grand Mean + Treatment_{i} + Replicate_{j} + Error_{ij}; with subscripts represented by _{}.

Treatment means were computed from ordinary least squares estimates of fixed treatment effects, with sums of squares computed sequentially from nested models (Schabenberger & Pierce, 2001). The SEM and CV% values as well as the level of significance are presented in the treatments mean tables. The significance level of 0.1, 1.0, and 5.0% are indicated with the SEM values; with 10% included for soil properties because some of these have inherently high variability.

To estimate the economic benefit of wood ash use, the yield and fertilizer cost differences between the ASH+N treatment and FRT were calculated (Table 7). Because the comparison was between only 2 of the 4 treatments, the differences were estimated without any statistical analyses. The extra crop yield from the ASH+N over the FRT treatment and the sale price of crops were used to calculate the income difference between the two treatments. Then the cost of fertilizers for the FRT treatment, except N Fertilizer used in both treatments, was added to estimate the contribution margin from wood ash application.

3. Results and Discussion

3.1 Wood Ash Properties

The dry wood ash had a bulk density of 0.624 t m^{-3} and a saturation water content of 900 g L^{-1}. Wood ash contained all essential plant nutrients, except N (Table 1). Considering the concentration of various nutrients, application of wood ash amounts to meet the P requirement of crops was considered sufficient to supply adequate amounts of essential plant nutrients, except N. This meant that wood ash could be used as a nutrient source for crops, when supplemented with N fertilizer. However, the nutrient content varies with the source of wood ash (Erich & Ohno 1992; Vance 1996). The %CCE of wood ash varied from 55 to 100% (Lickacz, 2002). In view of the above, chemical analysis to determine the concentrations of essential plant nutrients and CCE% is essential before making recommendations. Also, the limits set by the given jurisdiction to avoid negative effects on environment and on plant growth may have to be considered.

Table 2. Concentration of essential plant nutrients in wood ash

Nutrient	mg kg^{-1}	Nutrient	mg kg^{-1}
Calcium	324 000	Barium	1830
Potassium	69 000	Manganese	635
Magnesium	18 400	Boron	226
Phosphorus	7880	Copper	69
Iron	6900	Molybdenum	9
Sulphur	6580	Cobalt	6
Zinc	2860		

3.2 Soil Properties

The composite sample collected in May 2006 showed that the 0-15 cm soil had 51 g kg^{-1} organic matter, 5.7 pH, 9 mg NO_3-N kg^{-1}, 6.6 mg P kg^{-1}, 20 mg S kg^{-1}; and the 15-30 cm soil had 5 mg NO_3-N kg^{-1} and 9 mg S kg^{-1}.

Samples collected in May 2007, October 2008 and October 2013 indicated effects of wood ash application on several soil properties in the 0-15 cm soil depth only (Tables 3, 4 and 5), while little treatment influence was noticed in the 15-30 cm soil layer (data not presented).

The May 2007 samples reflected the effects of wood ash application in 2006. Compared to the CHK and FRT treatments, both the wood ash treatments had ($p < 0.05$) or tended to have ($p < 0.10$) higher pH, P, K, S, Ca, Ca/Mg ratio, Zn, B, and Mn levels in May 2007 (Table 3).

Table 3. Effects of the treatments applied in 2006, on the properties of 0-15 cm soil in May 2007

Measurement	CHK	FRT	ASH	ASH+N	^{z}SEM (9 df)	CV%
Organic matter, g kg^{1}	52	50	54	51	0.23ns	8.0
pH (water), units	6.0	5.8	6.3	6.3	0.13**	4.1
NO_3-N, mg kg^{-1}	9.8	13.7	9.7	12.3	2.08ns	33.6
Available P, mg kg^{-1}	17.2	18.5	21.0	17.7	2.01ns	19.9
Available K, mg kg^{-1}	156	172	194	190	15.4ns	15.9
SO_4-S, mg kg^{-1}	11.5	12.7	19.0	17.0	2.75ł	33.5
Ca, mg kg^{-1}	1645	1590	1990	1950	148.1 ł	5.9
Mg, mg kg^{-1}	504	496	516	502	21.9ns	3.1
Ca/Mg Ratio	3.26	3.20	3.86	3.88		
Na, mg kg^{-1}	93	96	108	102	12.2ns	8.7
Fe, mg kg^{-1}	162	160	148	146	8.2ns	3.8
Cu, mg kg^{-1}	0.78	0.84	0.82	0.80	0.050ns	4.4
ZN, mg kg^{-1}	2.72	2.74	5.23	4.90	1.053ł	19.2
B, mg kg^{-1}	0.65	0.65	0.90	0.75	0.095ł	9.2
Mn, mg kg^{-1}	7.17	7.58	5.15	5.98	0.763ł	8.3

Note. ^{z}In the SEM column, ***, **, * and † refers to treatment effect being significant at 0.1, 1, 5 and 10% significance level, respectively; and ns being not significant at 10% significance level.

The October 2008 and 2013 samples reflected the effects of wood ash application in both 2006 and 2007. The soil samples collected in October 2008 showed that both the wood ash treatments had or tended to have higher pH, P, K, S, Ca, Ca/Mg ratio, Cu, Zn, B, and Mn than both the CHK and FRT treatments (Table 4). Similarly, the set of soil samples collected in October 2013 also showed the ASH and ASH+N treatments had or tended to have higher pH, P, K, Ca, Ca/Mg ratio, Cu, Zn, B and Mn levels than both the CHK and FRT treatments (Table 5). For all the tested soil properties, there were no consistent differences between the CHK and FRT treatments as well as between the ASH and ASH+N treatments.

The soil properties data clearly showed the effects of wood ash application in 2006 and 2007 up to 2013. Actually the averages of differences between the wood ash (ASH & ASH+N) and other (CHK & FRT) treatments were generally greater in 2013 than in 2008. For example, the averages of differences in 2013 were greater than those in 2008 by 0.54 units pH, 8.5 mg P kg^{-1}, 24 mg K kg^{-1}, 280 mg Ca kg^{-1}, 0.55 Ca/Mg ratio, 3.51 mg Zn kg^{-1}, and 0.06 mg B kg^{-1}. These data showed that the wood ash effects on soil properties tended to be enhanced with time, indicating likelihood of the effects to last few more years.

Table 4. Effects of the treatments applied in 2006 and 2007, on the properties of 0-15 cm soil in October 2008

Measurement	CHK	FRT	ASH	ASH+N	^{z}SEM (9 df)	CV%
Organic matter, g kg^{-1}	40	44	42	41	0.47ns	8.0
pH (water), units	6.2	5.6	6.8	6.7	0.80***	0.9
NO_3-N, mg kg^{-1}	13.5	33.0	24.0	47.5	7.81*	18.8
Available P, mg kg^{-1}	23.5	29.5	35.0	39.0	7.47ns	16.8
Available K, mg kg^{-1}	96.5	93.5	161.5	175.5	30.23ł	16.3
SO_4-S, mg kg^{-1}	13.5	12.5	16.0	17.0	2.37ns	11.4
Ca, mg kg^{-1}	1485	1345	1655	1715	44.1***	2.0
Mg, mg kg^{-1}	445	432	432	432	21.6ns	3.5
Ca/Mg Ratio	3.33	3.11	3.83	3.97		
Na, mg kg^{-1}	75	102	118	117	21.1ns	14.6
Fe, mg kg^{-1}	91	98	92	94	4.8ns	3.6
Cu, mg kg^{-1}	0.55	0.60	0.80	0.75	0.215ns	22.6
ZN, mg kg^{-1}	3.55	3.50	8.60	9.55	1.211*	13.7
B, mg kg^{-1}	0.65	0.50	0.45	0.80	0.309ns	36.6
Mn, mg kg^{-1}	8.0	9.0	10.5	11.0	0.95ł	7.0

Note. ^{z}In the SEM column, ***, **, * and † refers to treatment effect being significant at 0.1, 1,5 and 10% significance level, respectively; and ns being not significant at 10% significance level.

Our results are supported by earlier studies. In northern Europe, wood ash has been extensively used to improve forest productivity (Vance, 1996; Demeyer et al., 2001; Pitman, 2006). On an acid agricultural soil in northwest Alberta, lime and wood ash increased microbial biomass and C mineralization as well as changed the functional structure of bacterial communities (Lupwayi, Arshad, Azooz, & Soon, 2009); and the soil pH increase was in the order: wood ash = lime, while the order for available P and aggregation of soil was wood ash > lime (Arshad et al., 2012). In central Canada, wood ash increased pH, Ca, Mg, K and P but had little effect on microbial activity and biomass of a Brunisol and a Luvisol in an incubation study (Pugliese et al., 2014); and the liming products that significantly raised the soil pH also increased Ca, P and K concentrations in a 3 year field study (Lalande, Gagnon, & Riyer, 2009). In a 3-year field study on Gray Luvisol and Dark Brown Chernozem soils on organic farms in northeastern Saskatchewan, annual application of wood ash at 1 Mg ha^{-1} increased soil pH, extractable P, sulphate-S and exchangeable K; and tended to increase light fraction organic C and N in soil (Malhi, 2012a).

A reduction in soil acidity is considered to create a relatively favorable environment for microbial activity (Arshad & Gill, 1996) and accelerate mineralization of N and P from organic matter as well as increase solubility of P (Nyborg & Hyot, 1978; Arshad et al., 1997).

Table 5. Effects of treatments applied in 2006 and 2007, on the properties of 0-15 cm soil in October 2013

Location	CHK	FRT	ASH	ASH+N	[z]SEM (9 df)	CV%
	Organic matter, g kg^{-1}					
North	45.0	42.5	40.5	41.5	0.05*	0.8
Centre	42.5	41.0	38.5	39.0	0.08*	1.4
South	40.5	39.0	39.0	38.5	0.25ns	4.0
Mean	**42.7**	**40.8**	**39.3**	**39.7**		
	pH (1 soil : 3 water), units					
North	5.55	5.20	6.45	6.30	0.385*	4.7
Centre	5.25	5.10	6.15	6.25	0.261*	3.3
South	5.40	5.83	6.60	6.35	0.557ns	6.0
Mean	**5.38**	**5.38**	**6.40**	**6.30**		
	Available P, mg kg^{-1}					
North	22.0	23.5	36.0	38.0	6.94†	16.6
Centre	22.5	28.0	30.5	29.0	5.17ns	13.4
South	21.0	24.0	36.0	31.5	7.34ns	16.8
Mean	**21.8**	**25.2**	**34.2**	**3.8**		
	NO_3-N, mg kg^{-1}					
North	7.5	8.0	7.5	10.5	0.95†	8.1
Centre	15.5	21.0	15.5	16.0	7.03ns	29.3
South	11.0	10.0	7.0	8.0	2.03ns	14.7
Mean	**11.3**	**13.0**	**10.0**	**11.5**		
	Available K, mg kg^{-1}					
North	168	140	233	240	49.8ns	18.1
Centre	141	158	170	182	20.1ns	8.8
South	152	194	216	227	63.3ns	20.6
Mean	**154**	**164**	**206**	**216**		
	SO_4-S, mg kg^{-1}					
North	19.5	20.0	25.5	24.0	1.72*	5.5
Centre	22.5	25.5	20.5	19.5	5.97ns	18.9
South	19.0	24.0	31.0	26.0	7.60ns	20.7
Mean	**20.3**	**23.2**	**25.7**	**23.2**		
	Ca, mg kg^{-1}					
North	1345	1270	2090	2050	298.0†	14.2
Centre	1230	1270	1660	1690	151.1*	7.3
South	1205	1493	2100	2015	440.1*	16.6
Mean	**1260**	**1344**	**1950**	**1918**		
	Mg, mg kg^{-1}					
North	375	348	408	372	27.1ns	5.1
Centre	368	360	350	345	18.8ns	3.8
South	350	377	455	393	71.3ns	11.7
Mean	**364**	**328**	**404**	**370**		

	Ca/Mg, Ratio					
North	3.59	3.65	5.12	5.51		
Centre	3.34	3.53	4.74	4.90		
South	3.44	3.96	4.62	5.13		
Mean	**3.46**	**4.10**	**4.82**	**5.18**		
	Na, mg kg^{-1}					
North	75.0	72.5	79.5	76.0	7.29ns	6.9
Centre	64.0	68.0	68.5	60.0	7.78ns	8.4
South	64.0	64.0	107.0	76.0	41.3ns	34.4
Mean	**67.7**	**68.2**	**84.8**	**70.7**		
	Fe, mg kg^{-1}					
North	82.0	85.5	78.0	76.5	3.71ns	3.3
Centre	84.0	87.5	79.0	79.5	6.10ns	5.3
South	87.0	84.7	77.0	81.5	7.82ns	6.1
Mean	**84.3**	**86.6**	**77.8**	**79.2**		
	Cu, mg kg^{-1}					
North	0.60	0.60	0.85	0.80	0.049*	5.0
Centre	0.50	0.55	0.70	0.75	0.128^{ns}	14.6
South	0.55	0.67	0.70	0.80	0.230^{ns}	21.8
Mean	**0.55**	**0.61**	**0.75**	**0.78**		
	Zn, mg kg^{-1}					
North	3.05	2.70	9.55	11.25	4.209ns	45.1
Centre	2.80	3.75	6.90	7.30	1.618†	22.2
South	2.80	5.30	10.1	10.50	5.323ns	48.0
Mean	**2.88**	**3.92**	**8.85**	**9.68**		
	B, mg kg^{-1}					
North	0.30	0.15	0.45	0.50	0.080*	16.5
Centre	0.25	0.25	0.40	0.40	0.058†	12.6
South	0.20	0.27	0.60	0.50	0.155†	25.5
Mean	**0.25**	**0.22**	**0.48**	**0.47**		
	Mn, mg kg^{-1}					
North	12.5	12.0	12.5	11.5	0.49ns	2.9
Centre	11.0	14.5	11.0	12.5	1.72ns	10.0
South	10.5	11.3	13.0	11.5	3.62ns	20.2
Mean	**11.3**	**12.6**	**12.2**	**11.8**		

Note. ^{z}In the SEM column, ***, **, * and † refers to treatment effect being significant at 0.1, 1,5 and 10% significance level, respectively; and ns being not significant at 10% significance level.

3.3 Crop Production in Treatment Application Years (2006 and 2007)

In 2006 and 2007, the seed yields were in the order: ASH+N>FRT>ASH>CHK (Table 6). The increase in 2006 pea yield from all other treatments over the CHK was significant, which was 1.26 Mg ha^{-1} by the ASH+N, 0.95 Mg ha^{-1} by the FRT and 0.89 Mg ha^{-1} by the ASH treatments. Compared to CHK, the increase in 2006 barley yield was large and significant from the ASH+N (2.69 Mg ha^{-1}) and FRT (2.10 Mg ha^{-1}) treatments; whereas it was only 0.98 Mg ha^{-1} and not significant from the ASH treatment. Like barley yield in 2006, the improvement in 2007 oat yield over the CHK was significant from the ASH+N (1.74 Mg ha^{-1}) and FRT (1.18 Mg ha^{-1}) treatments, while it was not significant from the ASH (0.38 Mg ha^{-1}) treatment.

The increase in crop yield with ASH treatment over the CHK, even though not always significant, showed the benefits of wood ash. Also, the ASH+N produced an extra 0.31 Mg ha^{-1} of pea, 0.60 Mg ha^{-1} of barley, and 0.55 Mg ha^{-1}of oats over the FRT treatment. Even though these differences were not statistically significant, the crop yield results indicated that absence of P fertilization in the ASH+N treatment did not have a negative effect and rather wood ash application provided extra benefits over the P fertilization. Probably, the crops benefited from the combined effects of other essential plant nutrients present in wood ash as well as increase in pH, microbial biomass and improvement in the soil tilth (Arshad et al., 2012; Lupwayi et al., 2009).

Table 6. Effects of the treatments applied in 2006 and 2007, on the seed yield in different years

Location	CHK	FRT	ASH	ASH+N	^{z}SEM (9 df)	CV%
	2006 Barley seed yield, Mg ha^{-1} (application year)					
Centre (Peas)	3.98	4.92	4.87	5.24	0.349*	10.4
South (Barley)	3.75	5.85	4.73	6.45	0.450**	12.2
	2007 Oats seed yield, Mg ha^{-1} (application year)					
South	3.46	4.65	3.84	5.20	0.503*	14.6
	2008 Wheat seed yield, Mg ha^{-1} (residual effects)					
North	1.55	1.62	1.80	1.77	0.110ns	9.2
Centre	1.57	1.54	1.88	1.72	0.099*	8.3
South	1.75	1.64	1.89	2.07	0.114*	8.7
Mean	**1.62**	**1.60**	**1.86**	**1.85**		
	2010 Wheat seed yield, Mg ha^{-1} (residual effects)					
North	2.10	2.33	2.58	2.36	0.147ns	8.8
Centre	1.65	1.62	1.91	1.96	0.088†	6.9
South	1.64	1.71	1.82	1.85	0.162*	13.0
Mean	**1.80**	**1.89**	**2.11**	**2.06**		
	2012 Oat seed yield, Mg ha^{-1} (residual effects)					
North	3.86	4.22	4.63	4.51	0.230*	6.0
	2013 Canola seed yield, Mg ha^{-1} (residual effects)					
North	4.09	4.53	4.69	5.22	0.170***	5.2
Centre	3.30	3.20	4.14	4.15	0.109***	3.8
South	3.87	4.01	4.48	4.49	0.178*	5.7
Mean	**3.76**	**3.92**	**4.44**	**4.62**		
	2014 Canola seed yield, Mg ha^{-1} (residual effects)					
North	1.54	1.44	1.89	1.67	0.075***	6.5
Centre	1.04	0.98	1.38	1.29	0.079***	9.4
South	1.59	1.94	2.25	2.21	0.070*	5.7
Mean	**1.39**	**1.45**	**1.84**	**1.72**		

Note. ^{z}In the SEM column, ***, **, * and † refers to treatment effect being significant at 0.1, 1, and 5% significance level, respectively; and ns being not significant at 5% significance level.

Similar to our results, other studies have also indicated that wood ash increased the yields of seed and forage crops. Based on 16 site-year data, G. Lickacz and R. Panasiuk (personal communication) observed higher forage yield of timothy (*Phleum pretense* L.) + alfalfa (*Medicago sativa* L.) with wood ash than the lime + annual P fertilizer applications. Lickacz (2002) reported higher forage yield with wood ash than with lime plus P fertilizer, probably due to a more rapid change in soil pH. For an acid agricultural soil in northwest Alberta, the increase in yields of barley, canola and field pea were in the order: wood ash > lime (Arshad et al., 2012). Beneficial effects on barley biomass and canola seed yield with wood ash supplemented by N fertilizer were also observed in central Alberta (Patterson et al., 2004a, 2004b). In a 3-year field study on organic farms in northeastern

Saskatchewan, annual applications of wood ash alone at 1 t ha^{-1} tended to increase seed yield of barley on both Gray Luvisol and Dark Brown Chernozem soils, where Black Chernozem was suspected to be P-deficient and Gray Luvisol was suspected to be S-deficient (Malhi, 2012b). In a 4-year study on a S-deficient Gray Luvisol soil in northeastern Saskatchewan, annual applications of wood ash alone at 2 Mg ha^{-1} tended to increase seed yield of canola in 2 of 4 years, but seed yield increased substantially when N fertilizer was also applied along with wood ash (Malhi, Vera, & Brandt, 2013). In a 3-year study on a P-deficient thin Black Chernozem soil in northeastern Saskatchewan, annual applications of wood ash alone at 2 Mg ha^{-1}increased seed yield of barley moderately in all 3 years (significant in 1 year), but seed yield increased substantially and significantly in all 3 years when N fertilizer was applied along with wood ash (Malhi, Vera, & Brandt, 2014).

3.4 Residual Effects of Treatments on Crop Yield in 2008, 2010, 2012, 2013 and 2014

In 2008, both the ASH and ASH+N treatments produced more seed yield of wheat compared to both the CHK and FRT treatments, though the differences were not significant at North site (Table 6). Averaged across the 3 locations, both the ASH and ASH+N treatments produced 0.25 t ha^{-1} more wheat than the FRT treatment.

Like 2008, the ASH and ASH+N treatments consistently produced more wheat yield than the FRT treatment and CHK in 2010, with significant differences at the Centre and South sites (Table 6). Averaged across the 3 locations, the increase in wheat yield over the FRT was 0.17 and 0.22 Mg ha^{-1} for the ASH+N and ASH treatments, respectively.

In 2012, oat yields from the ASH and ASH+N treatments was significantly higher than the CHK, while the yield from FRT treatment yield was not significantly different from any of the other treatments (Table 6). The Ash and ASH+N treatments produced 0.42 and 0.29 Mg ha^{-1} more oats than the FRT treatment, respectively.

The 2013 canola yield from the ASH+N treatment was significantly greater than the CHK and FRT treatments at all the three sites (Table 6). The ASH treatment also had significantly greater canola yield than the CHK and FRT treatments at the Centre and South locations. Averaged across the 3 locations, the increase in canola yield for the ASH and ASH+N treatments over the FRT treatment was 0.52 and 0.70 Mg ha^{-1}, respectively.

In 2014, canola yield was significantly greater from the ASH+N and ASH treatments than the CHK and FRT treatments at all the three locations, except for the differences between ASH+N and CHK at North site (Table 6). Averaged across the 3 locations in 2014, the increase in canola yield from the ASH and ASH+N treatments, respectively, was 0.45 and 0.334 Mg ha^{-1}over the CHK; and it was 0.39 and 0.27 kg ha^{-1}over the FRT treatment.

During the 2008, 2010, 2012, 2013 and 2014 years, the differences in crop yields between the CHK and FRT treatments were relatively small and inconsistent, indicating little residual effect of fertilizer applications in 2006 and 2007 (Table 6).

Consistently greater crop yield from the ASH and ASH+N treatments compare to both the CHK and FRT treatment during the 2008 to 2014 clearly showed residual effects of the 2006 and 2007 wood ash applications for 7 years. Relatively small and inconsistent differences in crop yields between the ASH and ASH+N treatments indicated similar residual effects of both these treatments. In earlier studies, residual effects of wood ash on crop yield have been observed for 2 years (Patterson et al., 2004a, 2004b) and 3 years (Arshad et al., 2012). Residual effects of 13.5 Mg ha^{-1} lime application in 1970 were observed until 1993 (for 23 years), a period much longer than our study (G. Lickacz, personal communication).

3.5 Contribution Margin

The extra yield from the ASH+N over the FRT treatment ranged from 0.12 Mg $ha^{-1}$of 2010 wheat to 0.70 t $ha^{-1}$of 2013 canola (Table 7). The actual crop yields and the differences between ASH+N and FRT treatments were generally smaller in drier years of 2008, 2010 and 2014 than in other years that had adequate soil moisture levels (Table 1).

Table 7. Estimated extra contribution margin from the ASH+N over the FRT treatment, using the additional crop yield, estimated extra income from sale of these crops based on the prices given in table, and savings due to no P fertilizer in the ASH+N treatment

Year	Crop	Yield, Mg ha^{-1}	Price, C$ Mg^{-1}	Income, C$ ha^{-1}
2006	Barley	0.598	98.3	58.8
2007	Oats	0.551	162.1	89.6
2008	Wheat	0.253	166.8	42.7
2010	Wheat	0.166	166.8	28.0
2012	Oat	0.288	162.1	46.2
2013	Canola	0.704	406.1	284.3
2014	Canola	0.272	406.1	111.7
Extra income from additional crop yield				661.3
P fertilizer price (32 kg ha^{-1} in 2006 & 2007, @ $2.80 kg^{-1} P) savings				89.5
Total (extra income + saving)				750.8

When combined with sale prices of crops, the extra income from the ASH+N over the FRT treatment ranged from \$28.0 ha^{-1} in 2010 to \$284.3 ha^{-1} in 2013. Thus a total extra income of \$661.3 ha^{-1} was realized in seven crop years.

Adding the differences in fertilizer costs between the ASH+N and FRT treatments in 2006 and 2007 ($89.50) to the extra income from crops provided contribution margin of \$750.80 ha^{-1} from the crops harvested during the study period. Considering wood ash application of 7.73 t ha^{-1}, the estimated contribution margin was \$97.10 ha^{-1} Mg^{-1} of wood ash applied in this study.

4. Summary and Conclusions

Wood ash contained all the essential plant nutrients, except N. Increases in pH and several nutrients in the soil clearly indicated that wood ash applications in 2006 and 2007 improved soil properties, with residual effects observed up to 2013 and likely to continue for few more years.

Increases in crop yields from the ASH treatment over the CHK, without concurrent N fertilizer application, and higher yield from the ASH+N treatment compared to the FRT treatment indicated that the crops benefited from the combined effects of nutrients present in wood ash and the change in soil pH (liming effect). Apparently, the improvement in soil properties was responsible for the increase in crop yields up to 2014.

The extra crop yield from the ASH+N than the FRT treatment, in the years of treatment applications (2006 and 2007) as well as during the following years, resulted in additional income of \$661 ha^{-1}. Also, there was a saving of \$89 ha^{-1}from no P fertilizer applied in 2006 and 2007. Total of the differences in income and saving resulted in a contribution margin of \$751 ha^{-1} from wood ash use, which provided benefit of \$97 Mg^{-1} wood ash applied.

Both the soil measurements and crop yield data showed residual effects of the wood ash applied in 2006 and 2007 plus potential of saving on the fertilizer costs for the crops. Continuation of crop yield increase up to 2014 and improvements in soil properties up to 2013 from wood ash use indicate that the benefits may continue for another few years. Use of wood ash to improve the properties and crop production potential of acidic soils can also save landfill costs that are not considered in present study. To estimate the total benefits from use of wood ash on acidic soils, it is suggested to consider the effects of wood ash during the years of application plus the residual effects in the following years and savings of landfill costs. Also being a natural material, it can be used in organic agriculture.

There is considerable variation in concentrations of plant nutrients and other elements in wood ash and the likelihood of wood ash having high concentrations of heavy metals. It is therefore suggested that future research studies and commercial use of wood ash should include analyses of plant nutrients and other elements (especially heavy metals) in wood ash, soil and grown crops, to avoid any environmental and safety issues from wood ash use.

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