ALKALINE INDUSTRIAL BY-PRODUCT EFFECTS ON PLANT GROWTH IN ACIDIC-CONTAMINATED SOIL SYSTEMS[1]

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Abstract. The objective of this research was to determine whether acidic-contaminated soil systems amended with alkaline industrial by-products enabled plant growth equivalent to that attained with a commercial grade mixture of $CaCO_3$ and CaO. In addition, it was determined whether an alkaline by-product dosage threshold existed, above which plant growth was impaired. Three types of cement kiln dust, three types of lime kiln dust, and two other alkaline by-products (Dicalcium Silicate, Carbide Lime) were applied to metalliferous tailings (pH 1.8) and a metal contaminated natural soil (pH 5.0) in a greenhouse pot study. Most alkaline products (pH 9.9 – 13.7) contained enriched metal concentrations of Al, As, B, Ba, Cd, Cr, Cu, Mn, Ni, Pb, Se and Zn. However, phytotoxic concentrations may have been mitigated i) when diluted in the soil profile at an application rate of 2 % to 10 % (soil dry weight basis), and ii) by the final amended soil pH in the range of 7.0 – 8.4 where these metals of concern were present at very low concentrations in the soil solution. All alkaline products produced a desired soil pH (7.0 – 8.4) in the root zone during plant growth tests. Following a 111-day plant growth period with Basin Wildrye (*Leymus cinereus*) and Redtop (*Agrostis alba*), all alkaline industrial by-products tested had plant growth equal to- or greater than- the $CaCO_3$/CaO mixture. For each alkaline industrial product, including the $CaCO_3$/CaO mixture, the greater the application rate, the less was the plant growth. Over the alkaline product dosage range of 0 % to 12 % (soil dry weight basis) the loss in aboveground plant biomass was 65 % for Basin Wildrye and 88 % for Redtop.

Additional Key Words: tailings, lime, contaminated soil, industrial by-products

Introduction

Due to absence of a market, many types of alkaline industrial by-products have historically been landfilled in the United States. Cement kiln dust (CKD) and lime kiln dust (LKD) are two of the most common alkaline by-products, but there are many others. In some regions of the

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United States, the near proximity of these alkaline by-products to acidic-contaminated landscapes in concert with low acquisition cost, make these by-products an attractive option for land reclamation projects.

Concern is present that alkaline industrial by-products contain metals and/or soluble salts that may impair plant growth when used to treat soil acidity (Portland Cement Association 1992, Daniels et al. 1996, Gitt and Dollhopf 1991, Kelly 1997). Alkaline by-products frequently emanate from a combustion process and contain ash from chemical additives and the fuel such as coal, coke, and others. We hypothesized that alkaline by-products with enriched metals and/or soluble salts may provide the means for good plant growth when applied at low soil application rates, but a threshold dosage rate may exist that impairs plant growth. This investigation was conducted to better understand these concerns.

Three types of CKD, three types of LKD, and two other alkaline by-products (Dicalcium Silicate, Carbide Lime) were evaluated in this investigation. These alkaline by-products, and the standard treatment composed of a commercial grade $CaCO_3$/CaO mixture, were applied to acidic-metalliferous soil matrices and plant growth evaluated. The objectives of this investigation were to i) determine the physicochemical traits of alkaline industrial by-products, ii) determine plant growth characteristics in acidic-metalliferous soil matrices amended with alkaline by-products and a $CaCO_3$/CaO mixture, and iii) determine whether an alkaline by-product dosage threshold exists, above which plant growth is impaired.

Methods

A synopsis of methods used will be presented below. Detailed methodology is presented in Dollhopf and Mehlenbacher (2001).

Three LKD by-products (Greymont, Tacoma, MT Limestone) were evaluated which were produced in the northwest United States in kilns heated by a coal/coke fuel mixture. Three CKD by-products were tested that were produced in Montana, two in kilns heated with a coal/coke fuel mixture (Holnam (Coal, Coke) and Ash Grove), and one kiln heated with natural gas (Holnam (CH_4)). In addition to limestone, amounts of shale, sand, glass, and an iron constituent were placed in the cement kiln, which may have in part contributed to CKD chemical composition. Dicalcium Silicate was a kiln dust by-product produced during manufacturing of magnesium from dolomite in the state of Washington. Carbide Lime was a by-product from the production of acetylene gas when coke was heated in the presence of CaO to produce calcium carbide, which is treated with water to yield acetylene and carbide lime. The $CaCO_3$/CaO mixture was composed of 60 % $CaCO_3$ and 40 % CaO (dry weight basis).

A bulk composite sample of mill tailings was collected from the Opportunity D-2 pond impoundment located near Anaconda, Montana. The sample was collected to a depth of 45 cm avoiding the initial 0 – 7 cm depth increment, which contained some, crushed limestone. The tailings material is a waste product from the processing of copper ore. Similarly, a bulk composite sample of contaminated soil was collected from the east end of Stucky Ridge near Anaconda, MT, within the 0 – 10 cm depth increment. This is a natural soil that has been impacted by adjacent smelting activities and subsequent smelter fallout for approximately 100 years. The MSU Plant Growth Center soil was composed of 33 % Bozeman silt-loam, 33 % sand, and 33 % sphagnum peat (volume basis). This soil served as both an optimal control and a growth media for the dosage rate trials.

Total metal analyses for tailings, contaminated soil, and lime products were determined with digestion in HNO_3 and H_2O_2, and the extract from a water-saturated paste was used to determine pH, electrical conductivity, sodium adsorption ratio, and soluble metal content. Particle size distribution was determined with a hydrometer using the modified Day method, while dry sieving was used to determine rock content of substrates. Lime requirement of tailings/contaminated soil substrates was determined with Equation 1 (Schafer and Associates and Reclamation Research 1987). The application rate of each alkaline product was adjusted for calcium carbonate equivalence, percent of oversize (> 0.25 mm) particles, and water content.

$$\text{t CaCO}_3/1000\text{ t soil} = (\%\text{HNO}_3\text{ ext. S} + \%\text{ Residual S})\ 31.25 + 23.44\ (\%\text{ HCL ext. S}) + \text{SMP Lime Requirement, t CaCO}_3/1000\text{ t soil} \quad (1)$$

The alkaline products were applied to the tailings and contaminated soil according to their respective adjusted lime requirement (Table 1). Lime products were applied to the Plant Growth Center soil at a rate of 0 % - 12 % (dry weight basis) (Table 2).

Following treatment of tailings, contaminated soil, and Plant Growth Center soil with each alkaline product, soils were infused with CO_2 gas for several months to facilitate carbonation

Table 1. Lime requirements for tailings and contaminated soil.

Treatment	Application Rate, t Amendment/1000 t Soil	
	Tailings	Contaminated Soil
1) Control	0	0
2) $CaCO_3/CaO$	29.16 $CaCO_3$ + 11.23 CaO	4.36 $CaCO_3$ + 1.87 CaO
3) Greymont LKD	75.15	12.55
4) Tacoma LKD	116.60	19.47
5) MT Limestone LKD	91.25	6.24
6) Holnam (CH_4) CKD	53.31	8.90
7) Holnam (Coal, Coke) CKD	55.15	9.21
8) Ash Grove CKD	68.70	11.47
9) Dicalcium Silicate	42.35	7.07
10) Carbide Lime	73.84	12.33

Table 2. Dosage rate scheme for Plant Growth Center soil.

Treatment	Alkaline Amendment Dosage Sequence						
	0 %	2 %	4 %	6 %	8 %	10 %	12 %
	t Amendment/1000 t Soil						
1) $CaCO_3/CaO$	0	20	40	60	80	100	120
2) Greymont LKD	0	20	40	60	80	100	120
3) Tacoma LKD	0	20	40	60	80	100	120
4) MT Limestone LKD	0	20	40	60	80	100	120
5) Holnam (CH_4) CKD	0	20	40	60	80	100	120
6) Holnam (Coal, Coke) CKD	0	20	40	60	80	100	120
7) Ash Grove CKD	0	20	40	60	80	100	120
8) Dicalcium Silicate	0	20	40	60	80	100	120
9) Carbide Lime	0	20	40	60	80	100	120

reactions, which caused the soil pH to regress from 10 – 12 to < 8.4. Soil materials were fertilized with 30 mg/kg (60 lb/acre) N, 8 mg/kg (16 lb/acre) P, and 100 mg/kg (200 lb/acre) K. Amended tailings/soil material was placed in pots 15 cm deep and 15 cm in diameter and seeded with perennial grasses Basin Wildrye (*Leymus cinereus*, Magnar) and Redtop (*Agrostis alba*, Streaker). Fifteen seeds of the same plant species were planted in each pot. Following 14 days of post-emergence plant growth, several growth characteristics were measured and then plants were thinned to five per pot. Plants were grown with 18 hours of light per day at 21^{o} C. Night temperatures were maintained at 18^{o} C. Pots were configured into a randomized complete block experimental design that included 9 alkaline products and a non-amended control, 3 substrates (tailings, contaminated soil, and Plant Growth Center soil), two plant species, and 8 replications. Pots received 100 ml of water per day. Following a 111-day growth period, above- and below-ground plant biomass was determined on a dry weight basis. Analysis of variance and linear regression were applied to data sets and tests of significance were applied at the 0.05 probability level. Data that failed normality were transformed to normally distributed data prior to tests of significance.

The MSU Plant Growth Center soil was used as the potting medium to evaluate effects of increasing alkaline product dosage rate on plant growth. Each of the nine alkaline products was applied to this growth medium at the following 7 application rates (dry weight basis): 0 %, 2 %, 4 %, 6 %, 8 %, 10 %, 12 %. This experiment utilized the same 2 plant species mentioned previously, was configured into a randomized complete block design, and was replicated 5 times. Plant growth and harvest procedures were the same as described above.

Results and Discussion

Chemical Traits of Tailings and Contaminated soil

The sandy loam tailings were acidic (pH 1.8) and saline (9.7 ds/m), had a total lime requirement of 47.43 t CaCO3/1000 t of which 19.2 t $CaCO_3$/1000 t was required to neutralize the active acidity and potential acidity emanating from sulfide minerals (0.51 %) required 15.9 t $CaCO_3$/1000 tons. Tailings contained enriched levels of metals including Al, Cu, Mn, and Zn (Table 3). The contaminated natural soil had a sandy loam texture and rock fragment content of 23 %, pH 5.0, was not saline, and had enriched total concentrations of As (443 µg/g), Cu (1400 µg/g), Pb, Mn, and Zn due to approximately 100 years of smelter emissions (Table 3). The contaminated soil had a total lime requirement of 7.92 t CaCO3/1000 t of which 5.4 t CaCO3/1000 t was required to neutralize the active acidity and potential acidity emanating from dry deposition of sulfates and sulfide minerals (0.03 %) required 0.94 t CaCO3/1000 tons. The MSU Plant Growth Center soil exhibited a pH range of 7.6 – 7.7 and it had no known limiting factors to plant growth.

Chemical Traits of Alkaline Industrial By-products

The pH of alkaline by-products ranged from 9.6 to 13.7. The calcium carbonate equivalence

Table 3. Physicochemical characteristics of tailings and contaminated soil.

Sample Type	**pH**	**EC (ds/m)**	**Sodium Adsorption Ratio**	**Water Saturated Paste Extract (mg/l)**					
				Al	**As**	**Cu**	**Pb**	**Mn**	**Zn**
Contaminated Soil	5.0	0.60	0.32	1	0.36	22.5	< 1	4.6	10.5
Tailings	1.8	9.7	0.03	976	6.8	99.0	< .01	183	81.4

Sample Type	**Total Concentration (mg/kg)**					
	Al	**As**	**Cu**	**Pb**	**Mn**	**Zn**
Contaminated Soil	11400	443	1400	138	241	311
Tailings	2680	76	162	273	93	94

of these alkaline by-products ranged from 69.1 – 127.0 %. CKD products were both saline (66.8 – 99.3 ds/m) and sodic (SAR 28.5 – 40.1). Conversely, LKD samples, Dicalcium Silicate, and Carbide Lime were neither saline (0.2 – 2.2 ds/m) nor sodic (0.02 – 1.8). CKD salinity may emanate from high concentrations of water-soluble SO_4^{2-} (15300 – 48100 mg/l) and Cl^- (1070 – 1180 mg/l) in association with the cations Ca^{2+}, Mg^{2+}, Na^+, and K^+ (Table 4).

Total V was enriched 2 – 65 times in LKD and CKD compared to the control alkaline product, i.e. $CaCO_3$ (limestone) and CaO (quicklime). Total Al was enriched 2 – 30 times in alkaline industrial by-products compared to the control (limestone and quicklime). Dicalcium Silicate contained the greatest concentration of total Al (67,100 mg/kg). The associated water saturated paste extract for Dicalcium Silicate contained 464 mg/l Al, while all other alkaline industrial by-products contained < 2 mg/l. Total Ba was enriched in most kiln dusts by as much as 33 times compared to $CaCO_3$ and CaO. Total B was enriched in Greymont LKD (137 mg/kg) and Montana Limestone LKD (130 mg/kg) approximately 50 times compared to the control materials. Total Se was not enriched in alkaline industrial by-products, but the water extract from a saturated paste was enriched several hundred times in CKD compared to the control. CKD by-products were enriched 12.2 to 25.9 times for total Zn, while LKD enrichment was 1.3 to 3.8 times that compared to the control. In general, both LKD and CKD had enrichment in As, Cd, Cr, Cu, Pb, Mn, and Ni compared to the control, while Dicalcium Silicate and Carbide Lime were not enriched in these elements (Table 4).

Alkaline industrial by-products often contained significantly high metal concentrations, which may contribute to toxicity in plants. However, these concentrations may be mitigated when i) applied to the soil at an application rate of 2 – 10 % of the soil mass which facilitates dilution of the metal and ii) the change in amendment pH from a range of 9.6 – 13.7 to a soil pH of 7.0 – 8.4

Table 4. Physicochemical characteristics of alkaline industrial by-products and commercial grade lime

Sample Type	**Water Saturated Paste Extract (mg/l)**							
	Al	**As**	**B**	**Pb**	**Se**	**Zn**	**SO_4**	**Cl**
Greymont LKD	< 1	< 0.01	< 1	< 0.01	0.05	< 0.1	1380	160
Tacoma LKD	< 1	< 0.01	< 1	< 0.01	< 0.01	< 0.1	7	22
MT Limestone LKD	< 1	< 0.01	< 1	< 0.01	0.09	< 0.1	1680	279
Holnam (CH_4) CKD	< 2	0.55	5	0.7	3.31	1.3	15300	1070
Holnam (Coal, Coke)	< 2	0.03	< 2	0.02	0.1	< 1	28100	1050
Ash Grove CKD	< 1	0.36	< 1	0.2	1.3	1.9	48100	1180
Dicalcium Silicate	464	< 0.01	< 1	< 0.01	0.01	< 0.1	< 1	3
Carbide Lime	< 1	< 0.01	< 1	< 0.01	0.01	< 0.1	5	87
$CaCO_3$	< 1	< 0.01	< 1	< 0.01	< 0.01	< 0.1	59	43
CaO	< 1	< 0.01	< 1	< 0.01	< 0.01	< 0.1	134	6

Sample Type	**Total Concentration (mg/kg)**											
	Al	**As**	**B**	**Ba**	**Cd**	**Cr**	**Cu**	**Mn**	**Ni**	**Pb**	**V**	**Zn**
Greymont LKD	16300	5	137	475	4	< 5	19	325	129	107	454	49
Tacoma LKD	2810	11	7	23	< 1	< 5	20	96	7	18	15	68
MT Limestone LKD	16300	< 5	130	862	1	42	13	228	< 5	9	18	23
Holnam (CH_4) CKD	12000	13	16	77	4	59	11	278	< 5	205	25	219
Holnam (Coal/Coke) CKD	11200	9	< 1	161	2	83	10	276	11	94	60	115
Ash Grove CKD	9380	15	20	131	5	33	45	247	13	117	43	467
Dicalcium Silicate	67100	< 5	< 5	24	< 1	< 5	< 5	7	< 5	< 5	< 5	< 5
Carbide Lime	3070	< 5	6	11	< 1	< 5	< 5	< 5	< 5	< 5	5	< 5
$CaCO_3$	794	< 5	< 5	17	< 1	< 5	< 5	85	< 5	< 5	7	10
CaO	1100	< 5	< 5	26	< 1	78	5	159	< 5	< 5	6	18

results in decreased solubility of many but not all metals. Further analytical research was performed to ascertain the behavior of Al and V in the soil matrix. Total concentration and water soluble extract for V and water soluble extract for Al was analyzed in tailings and contaminated soil after 111 days of plant growth. The total and soluble metal concentrations that were inherent in the soils and the alkaline amendments greatly decreased as a result i) the change in soil pH from a range of 1.8 – 5.0 to 7.0 – 8.4 and ii) the change in pH of the alkaline product from a range of 9.6 – 13.7 to 7.0 – 8.4 (Table 5).

Alkaline industrial by-products will typically be applied to acidic-contaminated soil systems in the field at various application rates ranging up to 10 %, i.e. 100 tons amendment/1000 tons soil. There are treatment design risks when alkaline industrial by-products are used to amend acidic-contaminated soils. Additional metal contaminants are incorporated into the root zone and plant growth issues may arise if the soil pH migrates outside the 7.0 – 8.4 boundary condition in the future i.e. the soil re-acidifies.

Table 5. Vanadium and aluminum soil concentrations after 111 days of plant growth.

Sample Type	**Greymont LKD Application Rate tons/1000 tons**	**Total Concentration, V (mg/kg)**	**Water Saturated Paste Extract, V (mg/l)**
Tailings	75.15	41	< 0.5
Contaminated Soil	12.55	37	< 0.5

Sample Type	**Dicalcium Silicate Application Rate, tons/1000 tons**	**Water Saturated Paste Extract, Al (mg/l)**
Tailings	42.35	< 0.5
Contaminated Soil	7.07	1.3

Alkaline By-product Effects on Plant Growth

When tailings (pH 1.8) were not amended with an alkaline amendment, the result was no plant growth (Tables 6 and 7). When contaminated soil (pH 5.0) was not amended, mean plant growth was comparatively small. All alkaline products produced a desired pH (7.0 – 8.4) in the root zone during the plant growth tests.

Following a 111-day plant growth period for Basin Wildrye and Redtop, all alkaline industrial by-products tested had plant growth equal to- or greater than- the $CaCO_3$/CaO mixture. This was the case in tailings and the contaminated soil for above ground plant biomass and root biomass. Based on these data, it was recommended that alkaline industrial by-products discussed in this report be permitted for use in in-situ soil remediation projects. However, it is emphasized that the potential lower cost of alkaline by-products comes with the risk that additional metals will be introduced into the soil that may cause plant growth issues in the future if the soil pH migrates outside the 7.0 – 8.4 boundary condition.

Effect of Increasing Application Rates of Alkaline Products on Plant Growth

It was hypothesized that alkaline products have a threshold application rate above which plant growth is significantly impaired. For example, good plant growth resulted when acidic-metal contaminated tailings and soil were amended with Dicalcium Silicate (Table 6). However, previous reports indicated Dicalcium Silicate increased soil pH and precipitated metal contaminants from solution (Dollhopf, et al. 1996; Dollhopf and McDaniel, 1997), but plant growth failed in amended acid mine waste materials (Kelly 1997). All these investigations used acidic-metalliferous tailings from the Opportunity impoundment located near Anaconda, Montana. However, tailings material collected by Kelly (1997) required a Dicalcium Silicate application rate of 196 tons/1000 tons of tailings, while the required application rate in this investigation was 42.4 tons/1000 tons of tailings. These results indicate that Dicalcium Silicate applied to a soil at a rate of 4.2 % (dry weight basis) enabled good plant growth, but an application rate of 19.6 % resulted in very poor plant growth. This suggests there is a threshold application rate for Dicalcium Silicate below which plant growth is good and above which plant growth will fail. Similarly, Daniels et al. (1996) evaluated an industrial lime by-product and reported a threshold application rate for soil above which plant growth was impaired.

For any alkaline product, including the $CaCO_3$/CaO mixture, the greater the application rate the less will be the plant growth (Figure 1). Starting with an ideal soil matrix (Plant Growth Center soil) for plant growth with an initial pH range of 7.6 – 7.7, each 2 % increase in the alkaline amendment application rate caused an incremental decrease in above ground biomass, following the 90 day plant growth period. Across the amendment application range of 0 % to 12 % the loss in plant biomass was 65 % for Basin Wildrye and 88 % for Redtop. The greater the excess of alkaline amendment residing in the soil matrix to address future potential acidity issues, the greater was the loss in plant growth.

The progressive loss in plant biomass with increasing alkaline product application rate, illustrated in Figure 1, is not consistent with the threshold concept. A typical threshold would be expressed by similar plant biomass values with increasing alkaline product application, followed by an abrupt decline in plant biomass at the threshold application rate. The principle presented in Figure 1 is that for each alkaline product there will be a steady progressive decline in plant growth as a function of increasing amendment application rate.

Table 6. Effect of different alkaline products on growth of Basin Wildrye and Redtop 111 days after seeding.

Basin Wildrye	**Above Ground Biomass (g)**	**Below Ground Biomass (g)**
Amendment Type	**Tailings**	
Greymont LKD	0.492 a[†]	0.969 ab
Tacoma LKD	0.547 a	1.325 a
MT Limestone LKD	0.193 bc	0.526 b
Holnam (CH_4) CKD	0.31 abc	0.467 b
Holnam (Coal, Coke) CKD	0.397 ab	0.922 ab
Ash Grove CKD	0.143 bc	0.268 b
Dicalcium Silicate	0.566 a	1.482 a
Carbide Lime	0.152 bc	0.299 b
$CaCO_3$/CaO	0.068 c	0.261 b
Control	None	None
	Contaminated Soil	
Greymont LKD	0.620 a	0.646 ab
Tacoma LKD	0.616 a	0.934 a
MT Limestone LKD	0.530 ab	0.717 ab
Holnam (CH_4) CKD	0.495 ab	0.844 ab
Holnam (Coal, Coke) CKD	0.423 ab	0.461 abc
Ash Grove CKD	0.447 ab	0.358 abc
Dicalcium Silicate	0.417 abc	0.556 abc
Carbide Lime	0.262 bc	0.452 abc
$CaCO_3$/CaO	0.232 bc	0.258 c
Control	0.073 c	0.023 c
Redtop	**Above Ground Biomass (g)**	**Below Ground Biomass (g)**
Amendment Type	**Tailings**	
Greymont LKD	0.389 ab[†]	0.566 c
Tacoma LKD	0.935 a	1.793 a
MT Limestone LKD	0.128 b	0.296 c
Holnam (CH_4) CKD	0.310 ab	0.467 c
Holnam (Coal, Coke) CKD	0.663 a	0.980 bc
Ash Grove CKD	0.106 b	0.150 c
Dicalcium Silicate	0.621 a	1.385 ab
Carbide Lime	0.089 b	0.164 c
$CaCO_3$/CaO	0.180 b	0.108 c
Control	None	None
	Contaminated Soil	
Greymont LKD	0.370 bc	0.424 b
Tacoma LKD	1.341 a	1.314 a
MT Limestone LKD	0.825 b	0.608 b
Holnam (CH_4) CKD	0.630 bc	0.719 b
Holnam (Coal, Coke) CKD	0.703 bc	0.837 b
Ash Grove CKD	0.460 bc	0.340 b
Dicalcium Silicate	0.784 b	0.793 b
Carbide Lime	0.365 bc	0.356 b
$CaCO_3$/CaO	0.198 c	0.362 b
Control	0.031 c	0.021 b

[†] Means (n = 8) followed by the same letter in the same column for each substrate are not significantly different (P = 0.05).

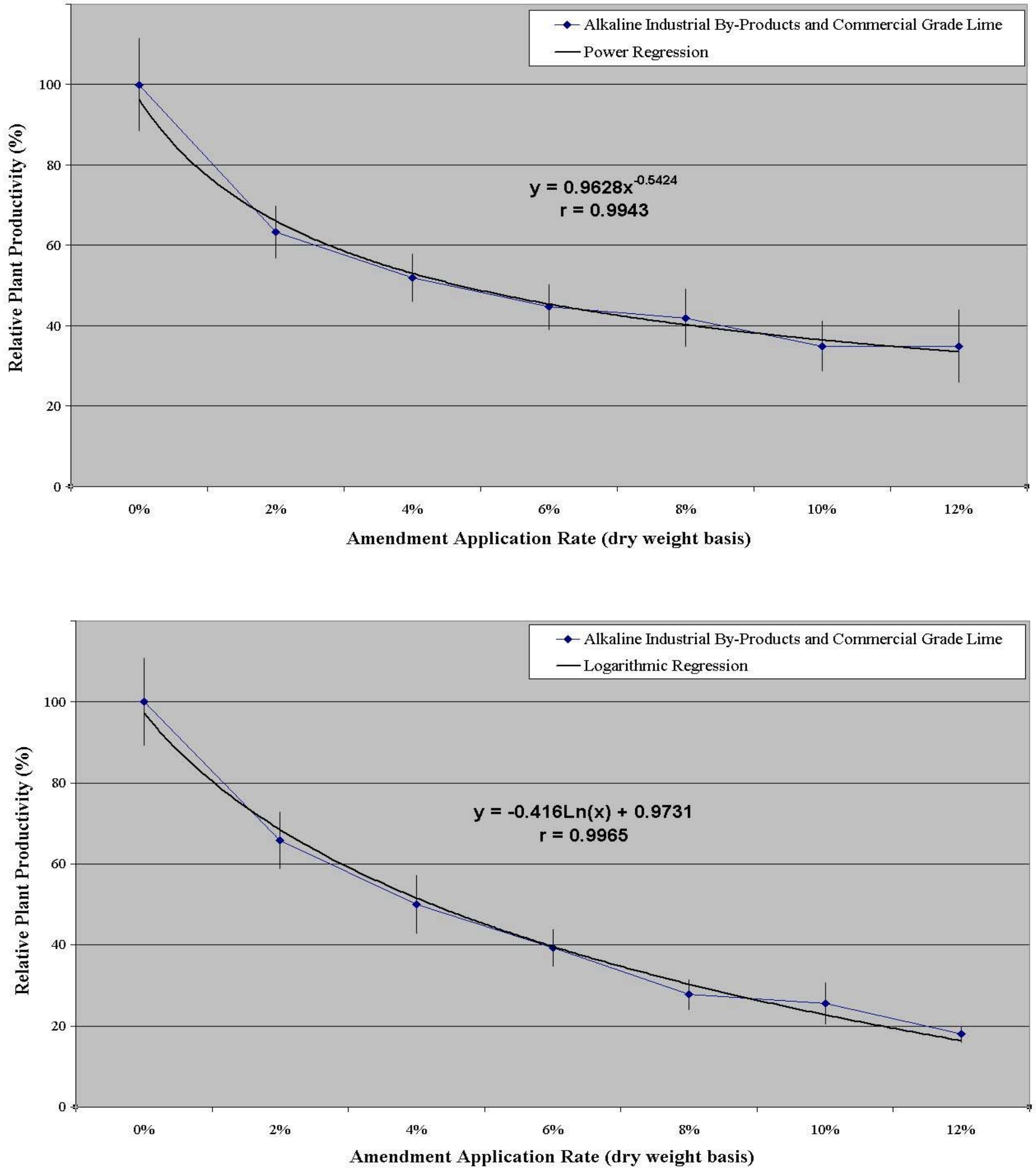

Figure 1. Loss in above ground biomass, Basin Wildrye (top) and Redtop (bottom), with increasing application of alkaline amendments. Each point is a mean of 45 observations (9 alkaline products, 5 replications and error bars represent plus or minus one standard deviation.

Loss in above ground plant biomass was significantly correlated (r = 0.62 and 0.56) to increased amendment application rate. Increased soil pH associated with greater amendment application rates was significantly correlated (r = 0.59 and 0.54) to loss in above ground plant biomass. The pH, measured at the start and cessation of the experiment, increased from approximately 7.7 – 8.3 across the alkaline amendment application rate range of 0 % to 12 %. Similarly, increased soil electrical conductivity (EC) associated with greater amendment application rates was significantly correlated (r = 0.54) to loss in above ground biomass. On the average, the soil EC increased from approximately 0.8 ds/m to 4.5 ds/m across the alkaline amendment application rate range of 0 % to 12 %. The three CKD amendments elevated the soil EC to a range of 7.08 ds/m to 16.63 ds/m for the 12 % amendment application rate. These results suggest that elevated soil pH and soluble salts associated with increasing alkaline amendment application rates contributed, in part, to the loss in plant biomass. The mechanisms causing loss in plant growth may have been i) lower availability of N, P, and K as pH increased and ii) greater expenditure of energy by the plant root to uptake water due to soluble salt induced increase in the osmotic potential.

Conclusion

Plant growth was evaluated in acidic-metalliferous tailings and acidic-metal contaminated soil after being neutralized with three lime kiln dust (LKD) industrial by-products, three cement kiln dusts (CKD) industrial by-products, industrial by-products Dicalcium Silicate and Carbide Lime, and a lime product mixture of $CaCO_3$/CaO. In addition, effects of increasing alkaline product dosage from 0 % to 12 % (soil dry weight basis) on plant growth in an optimal soil matrix were investigated.

Metals were often present in high concentrations in the alkaline by-product matrix which had a pH that ranged from 9.6 to 13.7. However, evidence indicated that plant growth issues may have been mitigated i) when diluted in the soil profile at a typical application rate of 2 % to 10% (soil dry weight basis) and ii) by an amended soil pH in the range of 7.0 – 8.4 when these metal contaminants were present at low concentrations in the soil solution. Treatment design risk is increased when alkaline by-products are used to amend soils. Additional metal contaminants are incorporated into the root zone and plant growth issues may arise if the soil pH migrates outside the 7.0 – 8.4 boundary condition in the future i.e. the soil re-acidifies.

All alkaline products produced a desired soil pH (7.0 – 8.4) in the root zone during plant growth test. Following a 111-day plant growth period for Basin Wildrye and Redtop, all alkaline industrial by-products tested had plant growth equal to- or greater than- the $CaCO_3$/CaO mixture. This was the case in tailings and the contaminated soil for above ground plant biomass and root mass. These results indicate the use of alkaline industrial by-products is a viable low cost alternative to limestone, hydrate lime and CaO. However, each industrial by-product should undergo a screening process that includes chemical characterization, and plant growth tests.

It was found that for every alkaline product, including the $CaCO_3$/CaO mixture, the greater the application rate, the less will be the plant growth. Starting with an ideal soil matrix (Plant Growth Center soil) for plant growth with an initial pH range of 7.6 – 7.7, each 2 % increase in the alkaline amendment application rate caused an incremental decrease in above ground plant biomass. Over the amendment application range of 0 % to 12 %, the loss in plant biomass was 65 % for Basin Wildrye and 88 % for Redtop. The greater the excess of alkaline amendment residing in the soil matrix, the greater was the loss in plant growth. This result was in part attributed to both elevated pH and soluble salts in the soil matrix. Therefore, when designing the alkaline amendment application rate for a project landscape, procedures should be used to apply the correct amount of alkaline material as opposed to a known excess. Excess applications emanate from insufficient data to account for variability across the landscape, thus more alkaline product is applied than required to insure the high rate captures this variability.

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