Anthroposol development from limestone quarry substrates

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Cohen-Fernández, A. C., Naeth, M. A. and Wilkinson, S. R. 2013. **Anthroposol development from limestone quarry substrates**. Can. J. Soil Sci. **93**: xxx–xxx. Limestone quarry reclamation worldwide requires development of substrates or anthroposolic soils. The suitability of three limestone substrates (gray, gray brown, crushed) for revegetation was assessed in two greenhouse experiments. In the first experiment amended substrates (pulp mill sludge, two manures, hay, straw, wood shavings, capping with two soils) alone and in combination with fertilizer and elemental sulfur were evaluated. Amendment rates were assessed in a second experiment. Plant density and above- and below-ground biomass were used to determine substrate suitability. The three limestone substrates supported germination, emergence and establishment of five native grasses when amended. Addition of fertilizer yielded three times more above-ground biomass and two times more below-ground biomass compared with the control, despite reducing plant density. Sulfur application did not significantly affect plant variables. Capped topsoil, clean fill and incorporated pulp mill sludge yielded the highest above-and below-ground biomass and plant density. To a lesser extent manure compost favorably changed plant parameters, but hay and straw did not. High fertilizer and amendment rates yielded better results than medium and low rates; pulp mill sludge was the exception with no significant difference in plant performance between low and high rates. Suitable anthroposols for limestone quarry reclamation were achieved.

Key words: Limestone substrate, native grasses, soil amendments

Cohen-Fernández, A. C., Naeth, M. A. et Wilkinson, S. R. 2013. **Développement d'un anthroposol sur les substrats d'une carrière de calcaire**. Can. J. Soil Sci. **93**: xxx–xxx. La restauration des carrières de calcaire dans le monde nécessite la création de substrats ou d'anthroposols. Les auteurs ont évalué l'utilité de trois substrats calcaires (gris, gris brun, pulvérisé) pour le rétablissement de la végétation, dans le cadre de deux expériences en serre. Dans la première, ils ont évalué le substrat bonifié (boue de papeterie, deux fumiers compostés, foin, paille, copeaux de bois, deux capuchons de sol) seul ou enrichi d'engrais et de soufre élémentaire. La deuxième a servi à établir l'importance de l'amendement. On a recouru à la densité de la végétation ainsi qu'à la biomasse sous et sur le sol pour déterminer dans quelle mesure le substrat se prêtait à la restauration. Les trois substrats calcaires ont permis la germination, la levée et l'établissement de cinq graminées indigènes après bonification. L'application d'engrais triple la biomasse aérienne et double la biomasse souterraine, bien qu'elle réduise la densité de la végétation. Le soufre n'a aucune incidence sensible sur les paramètres végétaux. L'addition d'un capuchon de sol de surface, un remplissage propre (sol de surface et sous-sol) et l'incorporation de boue de papeterie engendrent la plus forte production de biomasse aérienne et souterraine, de même que la végétation la plus dense. Le fumier composté améliore dans une moindre mesure les paramètres végétaux, mais tel n'est pas le cas du foin et de la paille. Un taux d'application élevé d'engrais et d'amendement donne de meilleurs résultats qu'un taux moyen ou faible, la boue de papeterie étant la seule exception. Dans ce cas, le rendement des plantes ne présentait pas de variation significative entre un taux d'application faible ou élevé. Il est possible de créer des anthroposols convenables pour la restauration des carrières de calcaire.

Mots clés: Substrat calcaire, graminées indigènes, amendement du sol

Limestone is a rock comprised mainly of calcium carbonate. Processed limestone is broadly used in a number of industries (Kesler 1994), prominently construction, and large amounts are necessary to meet the demand. The rock is extracted through extensive drilling and blasting, each quarry resulting in many hectares of drastically disturbed land. Often, hundreds of abandoned and active limestone quarries occur in single regions (Ontario Canada) (McLellan et al. 1979; Ontario Ministry of Natural Resources 2010) with multiple thousands around the world (Spalding et al. 1999; Bonifazi et al. 2003; Clemente et al. 2004; Allen et al. 2005).

Despite limestone quarry reclamation being an environmental necessity, its success has been limited (Bonifazi et al. 2003; Allen et al. 2005). Scarcity of soil can lead to attempts to reclaim directly on waste rock, but vegetation establishment on exposed calcareous material is unlikely due to low water- and nutrient-holding capacities. Chemical reactions with highly concentrated carbonates and high pH result in immobilized iron oxides, increased nitrification and limited available phosphorus due to phosphate precipitation, adsorption to carbonate minerals or insolubilization (Kishchuk 2000). Thus regulations and reclamation practices require inclusion of soil in the uppermost layers of contoured quarries; compliance with this poses a considerable problem for limestone quarry reclamation due to soil scarcity and poor soil quality.

Soil shortage may be addressed by creating a substrate suitable for vegetation with the abundant waste rock at limestone quarries. These substrates would be classified as anthroposols, azonal soils that have been highly modified or constructed by human activity, and are commonly built after disturbances as part of land reclamation activities (Naeth et al. 2012). If a suitable substrate can be created from limestone waste rock, soil may be required in smaller quantities, or even replaced in quarry reclamation. Physical and chemical properties of waste rock can be ameliorated with organic and chemical amendments, such as fertilizer, to support vegetation by increasing available nutrients. Soil pH can be decreased through sulfur application, which may result in increased nutrient availability. Amendments with high organic matter content can increase vegetation cover, microbial populations, nutrient cycling and mineral sources for plants (Noyd et al. 1996). Although many sources of organic amendments exist, local availability at the reclamation site is desired to manage costs. Use of industrial and municipal by-products, such as biosolids and sewage sludge, is economical and an alternative to their disposal in landfills. Sewage sludge has been used in limestone quarry reclamation, improving vegetation establishment (Moreno-Peñaranda et al. 2004; Almendro-Candel et al. 2007; Jimenez et al. 2007). Other amendments that improved soil properties in other reclamation scenarios, such as manure (Moss et al. 2002), municipal biosolids (Wester et al. 2003), pulp mill sludge (Eerden 1998) and softwood bark (Richardson and Evans 1986), should be evaluated.

Despite their beneficial effects, amendments may oversupply nitrogen, phosphorus or metals if applied at high rates. Adequate supplies of suitable amendments are often not available locally. Therefore, knowledge on how much amendment will be effective is required. Research has not determined whether low application rates can provide a substrate suitable for vegetation with decreased contamination risks. Use of native plant species adapted to limiting quarry conditions, and often required by regulations, will help retain biodiversity on the reclaimed area (Gerling et al. 1996; Lesica and Allendorf 1999; Martínez-Garza and Howe 2003).

This research was developed in two greenhouse sessions, where interactions at a small scale could be studied and evaluated prior to large-scale field implementation. The objectives of the first experiment were to determine if limestone quarry substrates from the same quarry differed in their ability to support vegetation and to identify readily available amendments that alone or in combination could ameliorate these substrates. The second experiment was designed to identify minimum application rates of amendments that would provide adequate establishment of a native grass mix. Effectiveness of amendments was evaluated using plant response variables.

MATERIALS AND METHODS

Limestone Substrate Materials and Amendments

Substrate materials were procured from Graymont Exshaw Quarry, near Kananaskis, Alberta, in the Mountain Forest Ecoregion. Limestone material not suitable for commercialization, consisting of waste rock mixed with overburden, was used in quarry backfilling and recontouring. Three types of limestone materials (crushed, gray, gray brown) were different in colour and processing. Crushed limestone ($<$9.5-mm particle size) was processed and commercialized; gray and gray brown limestone were residual unusable materials from blasting and processing ($\geq$40% rock fragments $>$9.5 mm); gray brown limestone was processed similarly to gray, but had higher content of soil particles from a B horizon of pH $>$8.8.

Eight organic amendments, alone and in combination with slow release nitrogen (NO_3) phosphorus (PO_4) – potassium (K) (14–14–14) fertilizer and elemental sulfur (S) (0–0–92), were used to ameliorate the limestone substrates. *Phleum pratense* L. (timothy) hay, *Hordeum vulgare* L. (barley) straw, beef manure compost, beef manure mix (2-yr-old 6:1:1 mix of manure, waste feed and wood chips), pulp mill sludge from Alberta Pacific Forest Product's kraft pulp mill wastewater treatment system, fine-screened wood shavings from *Pinus* sp. (pine) and *Picea glauca* (Moench) Voss (white spruce), topsoil and clean fill (topsoil with subsoil) were evaluated. The materials were locally available but limited; hence their use as amendments.

Limestone substrates and clean fill properties were determined in one composited sample per material. Chemical properties for manure compost and pulp mill sludge were determined in another project using the materials (Patterson 2008). All analyses were according to Carter (1993) unless otherwise noted. Sodium adsorption ratio, pH and electrical conductivity were determined in a 1:2 soil:water suspension. Total carbon (C) was determined by combustion; total organic and inorganic C by acid digestion then combustion. Total nitrogen (N) was determined by combustion and total organic N by Kjeldahl procedure (Kalra and Maynard 1991). Available NO_3, PO_4 and K were determined by modified Kelowna extraction (Qian et al. 1994) and available sulfate by extraction with 0.01 M calcium chloride. Cation exchange capacity was determined by barium chloride extraction. Particle size distribution was assessed by the hydrometer method.

Greenhouse Procedures and Experimental Design

Two 12-wk completely randomized, full-factorial greenhouse experiments were conducted. The first experiment evaluated the potential of amendments, fertilizer and sulfur to ameliorate limestone. Three levels of the factor limestone substrate (crushed, gray, gray brown) were tested with two levels of fertilizer (with, without), two levels of sulfur (with, without) and nine organic amendments (clean fill, topsoil, hay, straw, wood shavings, manure compost, manure mix, pulp mill sludge, unamended control). Each combined treatment was replicated four times (3 limestone substrates × 2 fertilizer levels × 2 sulfur levels × 9 organic amendments including a control × 4 replicates = 432 pots). Fertilizer was applied as pellets at 110 g m^{-2} (1.1 Mg ha^{-1}) and covered with 1.5 cm of treated substrate to avoid direct seed contact. Sulfur was applied to the surface at 50 g m^{-2} (0.5 Mg ha^{-1}). Topsoil and clean fill were placed as 5-cm layers on substrates, equivalent to 48 200 g m^{-2} (482 Mg ha^{-1}) and similar to field application. Other organic amendments were incorporated at field equivalent application rates: hay 350 g m^{-2} (3.5 Mg ha^{-1}), straw 350 g m^{-2} (3.5 Mg ha^{-1}), wood shavings 4500 g m^{-2} (45 Mg ha^{-1}), pulp mill sludge 4500 g m^{-2} (45 Mg ha^{-1}), manure compost 3000 g m^{-2} (30 Mg ha^{-1}) and manure mix 3900 g m^{-2} (39 Mg ha^{-1}). Rates were based on previous research in other harsh reclamation scenarios and on calculations so nitrogen and phosphorus did not exceed regulatory guidelines (Land Resources Network Ltd. 1983; Miller et al. 2000; Reid and Naeth 2005).

Grasses native to the area were selected to meet regulatory requirements and for adaptability to site conditions. Seeds of *Poa alpina* L. (alpine blue grass), *Agropyron trachycaulum* (Link) Malt ex H.F. Lewis. (slender wheat grass), *Elymus innovatus* Beal. (hairy wild rye), *Festuca saximontana* Rydb. (rocky mountain fescue) and *Trisetum spicatum* (L.) K. Richter (spike trisetum) were obtained from Brett-Young Seeds (Calmar, Alberta) and used in a mix. Treatments were placed in round plastic pots of 15 cm diameter by 19 cm height. Pots had four equidistant drainage holes at the bottom. Five seeds per species were seeded per pot. Pots were randomly located on the greenhouse bench where temperature was 21°C with a 16-h photoperiod. Tap water was applied with a watering wand with spray nozzle; pressure was manually regulated to avoid mechanical damage to plants. Since substrate in all treatments was rocky and drainage was high, watering was done daily.

In the second experiment, gray limestone, the most abundant material at Exshaw, was used as the substrate. Clean fill, wood shavings, manure compost and pulp mill sludge were incorporated at the same rates as in exp. 1 (high rate). To assess application amounts, half (medium rate) and a quarter (low rate) of the high rate were used (Table 1). The amount of straw in exp. 1 was used as low rate, then doubled for the medium rate and quadrupled for the high rate. Fertilizer was added to each amendment treatment at medium (55 g m^{-2}, 0.55 Mg ha^{-1}) and low (27 g m^{-2}, 0.27 Mg ha^{-1}) rates. All treatments were replicated five times (5 amendments × 3 amendment rates × 2 fertilizer rates × 5 replicates = 150 pots). Greenhouse procedures were similar to those of exp. 1.

Quantification of Plant Response and Statistical Analyses

Number of plants emerged was recorded 7 d after seeding and plant density and survival were recorded weekly from this point for 12 wk. At the end of each experiment, plants were clipped at ground level and roots were collected by hand separation from the substrate. Above- and below-ground biomass from each pot were oven-dried to a constant weight at 80°C for 48 h.

Plant density and above- and below-ground biomass data were analyzed with non-parametric permutational analysis of variance (PERMANOVA v.1.6) (Anderson 2001; McArdle and Anderson 2001), after verifying that data did not have normal distribution and equal variances. Permutation tests calculate probability of getting a value ≥ an observed value under a specific null hypothesis by recalculating the test statistic after random data reordering (Anderson 2001). A four-way non-parametric ANOVA was used in exp. 1, with fixed factors substrate, amendment, fertilizer and sulfur. Following significant three-way interactions, simple main effects (Keppel 1982; Woodward and Bonett 2011) were further analyzed. A three-way non-parametric ANOVA was used in exp. 2 with fixed factors amendment, amendment rate and fertilizer rate. Analysis was based on measures of Euclidean distances; 10 000 permutations of raw data were used in all tests (Larson et al. 2007; Chu et al. 2009). Post hoc pairwise comparisons were conducted with PERMANOVA for significant factors and interactions and Monte Carlo *P* values were used. A significance level of 0.05 was used for all tests.

Table 1. Application rates of amendments on gray limestone used in the second greenhouse experiment

	Application rate [g m^{-2} (Mg ha^{-1})]		
Amendment	High	Medium	Low
Fertilizer		55 (0.55)	27 (0.27)
Straw	1 400 (140)	700 (70)	350 (35)
Manure compost	3 900 (39)	1 950 (19.5)	975 (9.75)
Pulp mill sludge	4 500 (45)	2 250 (22.5)	1 125 (11.25)
Wood shavings	4 500 (45)	2 250 (22.5)	1 125 (11.25)
Clean fill	48 200 (482)	24 100 (241)	12 050 (120.5)

RESULTS

Plant Response to Limestone Substrates and Amendments (Experiment 1)

Three-way interactions were significant for plant density, above- and below-ground biomass (Table 2). To understand the nature of the interactions, simple main effects were analyzed.

Plants established in all substrates, with lower density in crushed limestone than in comparable treatments in gray or gray brown limestone (Fig. 1). The effects of amendment and fertilizer varied across substrates. Within crushed limestone, there was a significant interaction between amendment and fertilizer ($P = 0.0181$) for plant density; only main effects were significant for gray ($P = 0.0001$ both factors) and gray brown ($P = 0.0001$ for fertilizer; $P = 0.0045$ for amendment) limestone. Fertilizer significantly reduced plant density in gray and gray brown limestone (Fig. 1). In crushed limestone, fertilizer had a significant negative effect on density when added with hay, straw, manure compost or pulp mill sludge and no effect when added with other amendments. Addition of clean fill, topsoil, wood shavings or pulp mill sludge significantly increased density relative to the control in gray limestone, but only pulp mill sludge in gray brown limestone. Addition of topsoil, clean fill, straw and pulp mill sludge without fertilizer significantly increased plant density in crushed limestone relative to controls.

The effect of fertilizer on biomass was not dependent on substrate, but on amendment and sulfur. Across substrates, fertilizer alone with most organic amendments significantly ($P \leq 0.0030$) increased above-ground biomass (Fig. 2). The exception, where no significant effect was found, was manure compost. Similarly, across substrates, fertilizer alone significantly increased below-ground biomass with most amendments ($P \leq 0.050$), the exceptions where fertilizer had no effect were pulp mill sludge, manure mix and manure compost (Fig. 3). For hay-amended limestone with fertilizer, sulfur significantly ($P = 0.0485$) reduced below-ground biomass and without fertilizer addition significantly increased below-ground biomass ($P = 0.0485$). Regardless of substrate, there was a significant interaction between fertilizer and sulfur for topsoil ($P = 0.0217$) and manure compost ($P = 0.0446$). For both amendments, with fertilizer, sulfur resulted in significantly more above-ground biomass and without fertilizer, significantly less biomass.

The effect of sulfur addition on plant density was dependent on substrate and amendment (Table 2, Fig. 1). Sulfur significantly increased density ($P = 0.0264$) with crushed limestone; however, the biological effect was small (9 versus 8 plants). A significant interaction between amendment and sulfur occurred in gray brown limestone ($P = 0.0494$). Straw and pulp mill sludge with sulfur had significantly greater plant density than the control and without sulfur, hay, manure mix and manure compost had significantly lower plant density than the control. For above-ground biomass, a significant interaction between amendment and sulfur occurred within crushed limestone treatments ($P = 0.0001$) (Fig. 2). Sulfur significantly increased above-ground biomass when added with fertilized topsoil or pulp mill sludge but decreased biomass when added with fertilized wood shavings or unfertilized manure compost. Above-ground biomass in the control, hay and straw treatments with or without sulfur was considerably less in crushed limestone than in other limestones.

Table 2. Permutational analyses of variance values for plant density and above- and below-ground biomass of native grasses in exp. 1

		Plant density		Above-ground biomass			Below-ground biomass	
Source[z]	df	*F*	*P*	*F*	*P*	df	*F*	*P*
Substrate	2	2.18	0.11	5.58	0.004	2	0.68	0.51
Fertilizer	1	122.33	<0.001	274.4	<0.001	1	44.54	<0.001
Sulfur	1	3.31	0.06	1.38	0.23	1	0.72	0.39
Amendment	8	31.6	<0.001	43.51	<0.001	8	7.93	<0.001
Substrate × Fertilizer	2	4.44	0.01	1.27	0.28	2	0.43	0.66
Substrate × Sulfur	2	0.15	0.85	0.09	0.90	2	0.12	0.88
Substrate × Amendment	16	1.58	0.07	2.07	0.008	16	1.39	0.14
Fertilizer × Sulfur	1	0.79	0.38	3.95	0.04	1	0.12	0.73
Fertilizer × Amendment	8	4.12	<0.001	14.92	<0.001	8	5.21	<0.001
Sulfur × Amendment	8	1.67	0.10	1.68	0.10	8	1.37	0.20
Substrate × Fertilizer × Sulfur	2	0.64	0.53	0.53	0.59	2	0.16	0.85
Substrate × Fertilizer × Amendment	16	2.07	0.01	1.50	0.09	16	1.42	0.12
Substrate × Sulfur × Amendment	16	2.06	0.01	1.93	0.01	16	1.15	0.30
Fertilizer × Sulfur × Amendment	8	1.25	0.26	2.29	0.02	8	2.26	0.02
Substrate × Fertilizer × Sulfur × Amendment	16	0.84	0.63	1.24	0.22	16	0.85	0.62
Residual	324					216		
Total	431					323		

[z]Amendments are topsoil, clean fill, hay, straw, wood shavings, manure mix, manure compost and pulpmill sludge. Fertilizer, with and without. Sulfur, with and without.

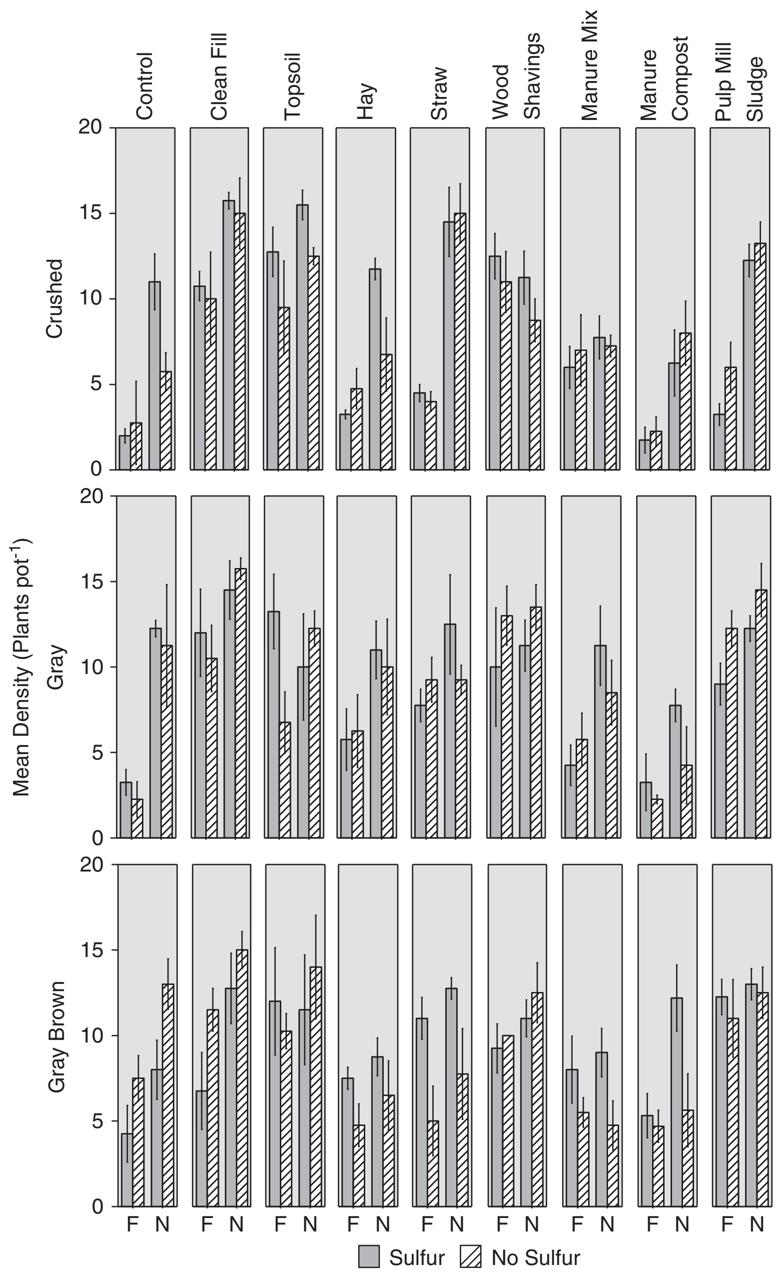

Fig. 1. Plant density response to fertilized (F) and unfertilized (N) amendment treatments. Error bars are ± standard error. $N = 4$.

Crushed limestone had higher fines content than gray or gray brown and slightly lower pH (Table 3). Manure compost had high electrical conductivity (19.7 dS m^{-1}) and sodium adsorption ratio (13.3). Total carbon, nitrogen and available nutrients were higher in manure compost and pulp mill sludge, than in clean fill; however, clean fill was still an equivalent (pulp mill sludge) or better (manure compost) amendment for plant establishment. Pulp mill sludge was a good source of nitrate (15.4 mg kg^{-1}) and phosphorus (191.3 mg kg^{-1}) and had high cation exchange capacity (20.2 meq 100 g^{-1}), which may improve nutrient retention.

Plant Response to Application Rates of Amendments and Fertilizer in Gray Limestone Substrate (Experiment 2)

Amendment significantly affected plant density ($P <$ 0.0100) with clean fill, wood shavings and pulp mill sludge having greater densities than manure compost and straw; plant density was not affected by amendment or fertilizer rates (Table 4, Fig. 4). Below-ground biomass was significantly affected by amendment, amendment rate and fertilizer rate ($P \leq 0.0010$ for all three factors) (Table 4). Below-ground biomass was significantly greater in clean fill and pulp mill sludge

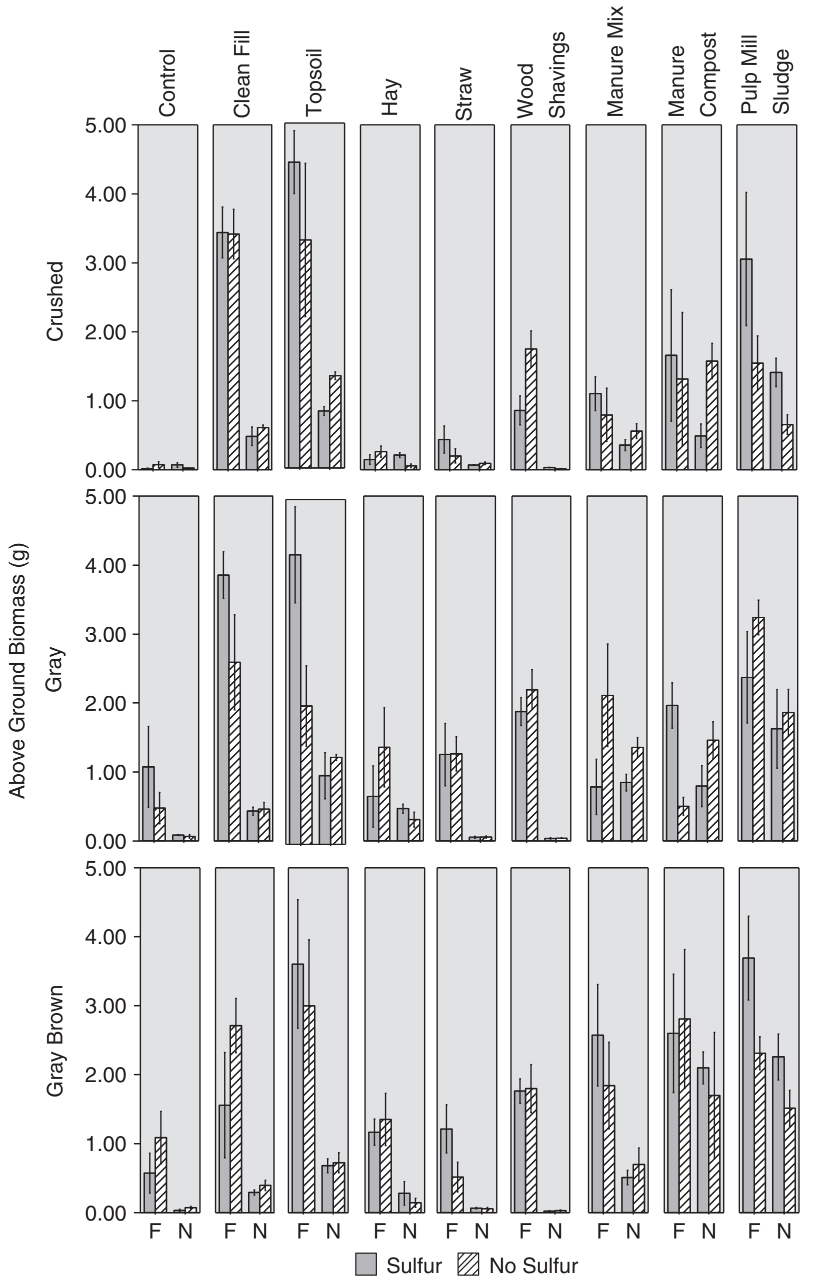

Fig. 2. Above-ground biomass in fertilized (F) and unfertilized (N) amendment treatments. Error bars are ± standard error. $N = 4$.

relative to straw or manure compost (Fig. 4). High amendment application rates and moderate fertilizer rates, independently, significantly increased below-ground biomass. For above-ground biomass, there were significant interactions between amendment and both rates (Table 4). Above-ground biomass in clean fill amended gray limestone was significantly greatest when applied at the highest rate (Fig. 5). Higher amendment rates also resulted in greater above-ground biomass for wood shavings, manure compost and pulp mill sludge but results were not significant. At low rates, clean fill and pulp mill sludge had significantly greater above-ground biomass than the other amendments, but not at other rates. Higher fertilizer rates increased above-ground biomass, significantly for clean fill. Straw treatments had the least below- and above-ground biomass regardless of amendment or fertilizer rate.

DISCUSSION

The three limestone substrates supported plant growth, showing potential for use in building anthroposols in quarries where mineral soil is in short supply. The

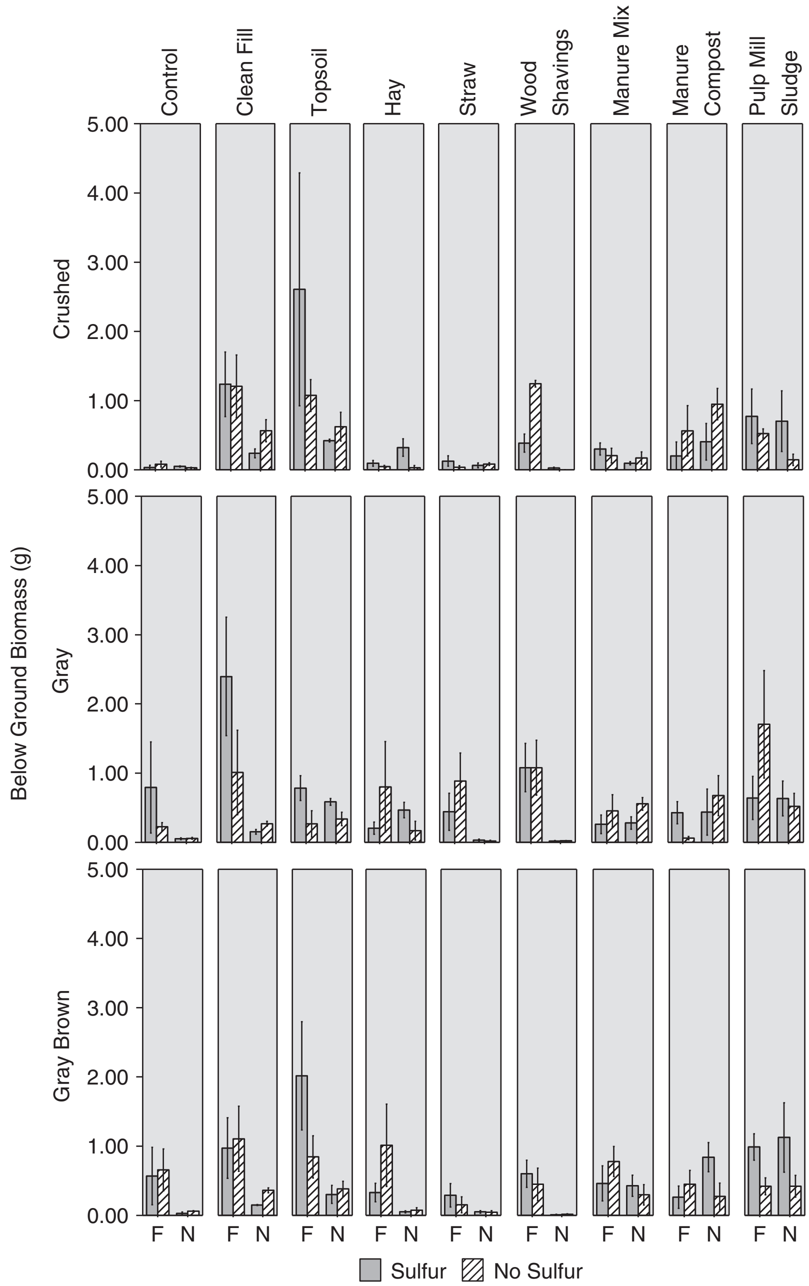

Fig. 3. Below-ground biomass in fertilized (F) and unfertilized (N) amendment treatments. Error bars are ± standard error. $N = 4$.

trajectory of pedogenesis of these soils in the field remains to be determined. If limestone-derived anthroposols can support a cover of vegetation, organic matter from plants should increase soil organic carbon and ultimately, soil development. Constructed substrates have been successfully used in other disturbance types and ecosystems, such as arctic diamond mines (Drozdowski et al. 2012).

Increased plant biomass with fertilizer alone or combined with amendments, shows the need to supplement low nutrient substrates. Higher biomass with topsoil, clean fill and pulp mill sludge is likely associated with their ability to hold water and nutrients (Shoenholtz et al. 1992). Proper fertilizer application (low amounts and single or few applications) to supplement other amendments will reduce dependence on fertilizer and risk of toxicity to plants (Gore and Godfrey 1981; Schoenholtz et al. 1992). Fertilizer may be most needed early in reclamation, as nutrients in organic materials become available and enhance nutrient-holding capacity. Fertilizer type and application could be tailored to address site limitations and requirements of different plant species. Increased native grass

Table 3. Particle sizes and pH of limestone substrate materials used in the greenhouse experiments

Particle size (%)	Crushed	Gray	Gray Brown
>9.55 mm	0.0	40.0	47.0
4 to 9.55 mm	53.3	31.6	29.3
Sand	27.5	16.3	20.2
Silt and clay	19.2	12.1	3.5
Hydrogen ion concentration (pH)	8.8	9.0	9.1

above- (Smika et al. 1965) and below-ground (Eissenstat and Cladwell 1988) biomass with fertilizer have been reported in other studies, despite adverse effects on seed germination for some species (Aerts and Berendse 1988; Bremner and Krogmeier 1989) and reduced plant density in this study. The response of seeds and plants to fertilizer is species specific (Sexsmith and Pittman 1963; Aerts and Berendse 1988; Sheppard et al. 2009). While little is known about the effects of fertilizer on native plants, in agriculture direct seed–fertilizer contact can reduce germination, and application following germination is preferred. Because seed sensitivity for species in this study has not been determined, impacts on seed germination are speculative.

In spite of not having a significant effect on response variables, sulfur application increased biomass of some species when used with topsoil and pulp mill sludge. These treatments had higher nutrient concentrations and sulfur may have increased availability of phosphorus, manganese and copper (Modaihsh et al. 1989) favoring species with higher nutrient demands. Ye et al. (2011) found that despite not reducing pH of a calcareous organic soil in South Florida, sulfur applied at 448 kg ha^{-1}, a rate similar to that in this experiment, significantly increased labile phosphorus concentrations 2 mo after application. In a naturally alkaline environment, sulfur could be used to increase nutrient availability from other amendments added, being more beneficial for species with higher requirements of, for example, phosphorus.

Topsoil, as a 5-cm layer, and clean fill, as a 5-cm layer or incorporated, likely modified the substrate by improving conditions for seed–soil contact, water- and nutrient-holding capacities and availability. Capping may have an advantage over incorporation by providing a better rooting environment and therefore improved water and nutrient uptake for newly establishing plants relative to mixtures of limestone and amendments. Overall, positive effects of topsoil or clean fill on grasses support the concept that available soil could be used in thinner layers over larger areas, but sustainable capping practices must be scientifically developed and evaluated based on disturbance type, site conditions, soil availability and end land use (Rowland et al. 2008; Jackson 2011).

Increased density and biomass of each species with pulp mill sludge in the greenhouse is highly desirable in the field. Pulp mill sludge had high cation exchange capacity and nutrient availability relative to other amendments. Significantly lower amounts of pulp mill sludge than soil required to achieve similar native grass biomass has significant implications for management, transportation and resource sustainability considering 45 and even 11 Mg ha^{-1} could have similar results to 482 Mg ha^{-1} of soil. Although pulp mill sludge did not appear to be beneficial for hardwood forest growth (Feldkirchner et al. 2002), other applications such as pulp mill effluents increased plant biomass (Patterson et al. 2009). Pulp mill sludge is worth assessing in other disturbances characterized by low nutrient- and water-holding capacities. Pulp mill sludge can be used in much lower quantities than soil with the added benefit that waste material is used instead of being disposed of in limited landfill space, ensuring nutrient and heavy metal loads comply with environmental standards. Potential lixiviation of nutrients and heavy metals at different application rates of pulp mill sludge could be investigated in future research.

Despite increased available nutrients with manure application (Tester 1990; Zingore et al. 2008) seed germination and/or plant growth may be negatively affected by increased electrical conductivity (Singh et al. 1997; Hao et al. 2003; Hao and Chang 2003). Although

Table 4. Permutational analyses of variance for plant density, above- and below-ground biomass of native grasses in treated gray limestone in exp. 2

		Density		Above-ground biomass		Below-ground biomass	
Source[z]	df	*F*	*P*	*F*	*P*	*F*	*P*
Amendment	4	24.60	<0.001	29.42	<0.001	16.65	<0.001
Amendment rate	2	0.27	0.750	9.23	<0.001	4.81	0.007
Fertilizer rate	1	1.18	0.270	9.91	0.001	6.32	0.001
Amendment × Amendment rate	8	1.63	0.120	2.00	0.050	0.99	0.450
Amendment × Fertilizer rate	4	1.27	0.280	1.08	0.360	0.34	0.840
Amendment rate × Fertilizer rate	2	2.12	0.120	3.33	0.030	2.05	0.120
Amendment × Amendment rate × Fertilizer rate	8	1.72	0.090	0.73	0.660	0.94	0.480
Residual	120						
Total	149						

[z]Amendments are clean fill, straw, wood shavings, manure compost and pulp mill sludge. Amendment rates are low, medium, high. Fertilizer rates are low, medium.

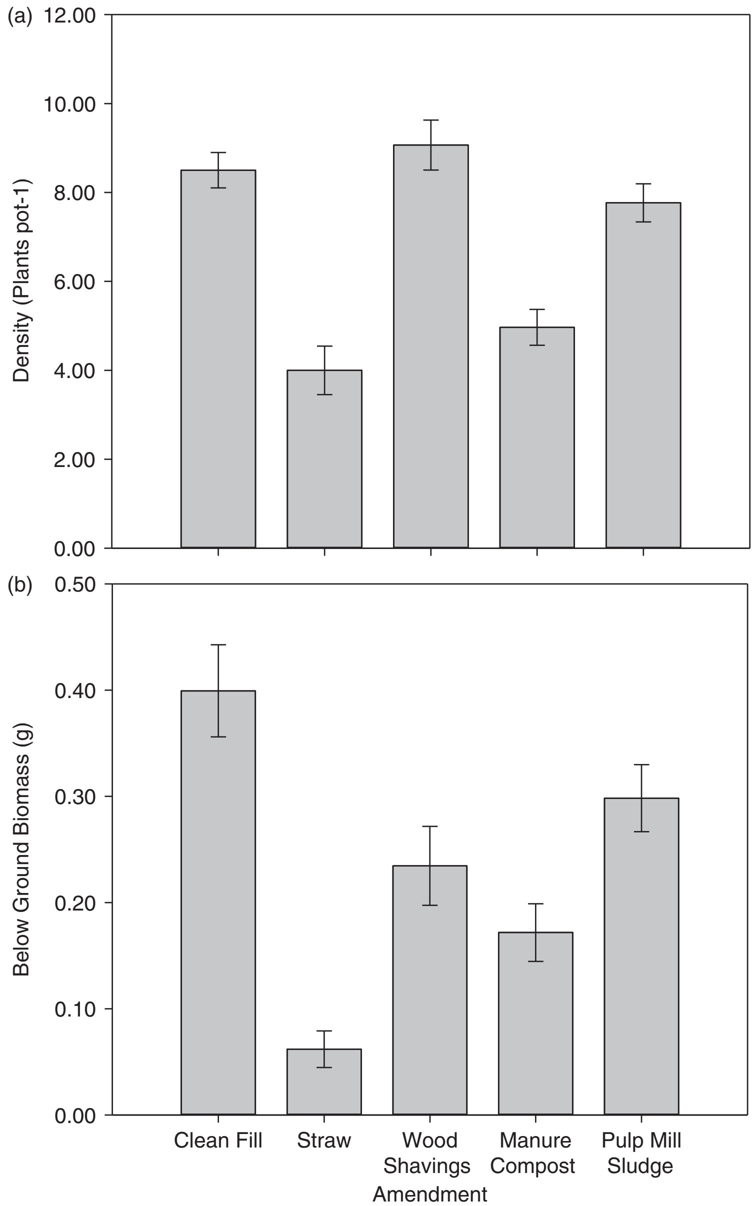

Fig. 4. Response of (a) plant density and (b) below-ground biomass to amended limestone. Error bars are ± standard error. $N = 5$.

manure treatments resulted in fewer plants and less above-ground biomass than fertilized topsoil, clean fill or sludge, in unfertilized treatments below-ground biomass was similar with manure, topsoil, clean fill and sludge, which is desirable to increase soil organic matter and stabilize quarry slopes. Electrical conductivity decreased quickly in the field (Cohen-Fernández and Naeth 2013); thus, benefits of increased organic matter with manure application outweigh lower germination and will be an asset for further substrate improvements.

The abundant but small-diameter roots of grasses grown in wood shavings treatments may be due to lower bulk density in the substrate which limited root growth and development by reducing anchoring and nutrient and water uptake, as concluded from the increased diameter with mechanical impedance in compacted or rocky soil (Clark et al. 2003). The high rate of wood shavings may not have been conducive to good root–substrate contact, but neither were lower rates. Thus, wood shavings may have limited benefits in limestone substrate amelioration, although it was better than hay and straw and not amending at all.

Hay and straw were not good amendments for limestone substrates as illustrated by the fewer plants and lower biomass than found in unamended substrates. The very low below-ground biomass could be related to phytotoxic damage caused when seedling roots came into close contact with straw (Lynch et al. 1980; Elliott

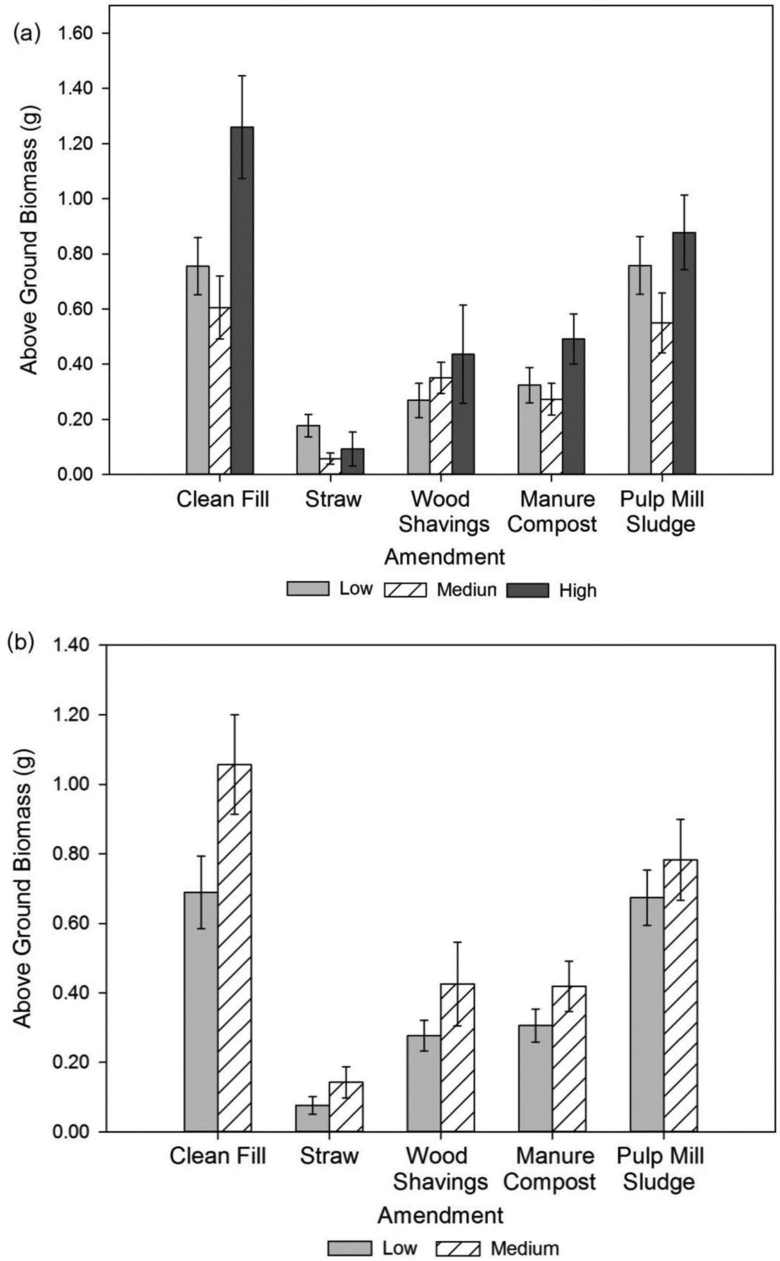

Fig. 5. Response of above-ground biomass to (a) amendment and amendment rates and (b) amendments and fertilizer rates. Error bars are ± standard error. $N = 5$.

and Lynch 1984). Lower plant biomass may be due to high carbon concentrations in hay and straw resulting in nitrogen immobilization. Henriksen and Breland (1999) found nitrogen requirement for optimum decomposition of straw was 1.2% of dry matter. Therefore, higher applications of nitrogen as fertilizer or organic amendment would be required to improve plant growth in straw and hay amended substrates (Land Resources Network Ltd. 1983; Davis et al. 1985; Richardson and Evans 1986).

Plant species responded differently to amendments and amendment rates but, in general, fertilizer, topsoil, clean fill and pulp mill sludge improved biomass, height and density of species tested (data not shown). Plant species differ in nutrient uptake abilities and growth responses to nutrient availability (Andrews and Robins 1969; Chu et al. 2009). Even though this research focused on a small number of species likely to be used in limestone quarry reclamation, successful treatments were beneficial for all species used.

CONCLUSIONS

Based on this research, limestone waste and crushed rock can be used as a suitable substrate for plant growth if ameliorated with fertilizer combined with organic amendments; essentially anthroposols can be built with limestone waste rock. A fertilizer formulation with nitrogen and phosphorus, such as slow release (14:14:14 nitrogen–phosphorus–potassium), is recommended at a rate of 110 g m^{-2} (1.1 Mg ha^{-1}), and no lower than 55 g m^{-2} (0.55 Mg ha^{-1}). Topsoil and clean fill, incorporated or as capped amendments, will increase limestone substrate suitability for native grass establishment, increasing above- and below-ground biomass, even if capping is only 5 cm thick, equivalent to 48 200 g m^{-2} (482 Mg ha^{-1}). Lower rates may result in poor plant performance. Pulp mill sludge has great potential for limestone substrate amelioration. Even the low application rate of 1100 g m^{-2} (11 Mg ha^{-1}) may result in similar vegetation responses to those in substrate ameliorated with soil. However, 4500 g m^{-2} (45 Mg ha^{-1}) application rate is recommended to provide substrate and plants with more organic matter, nutrients and increased water holding capacity. Amending with manure mix, manure compost and wood shavings may yield less above- and below-ground biomass of native grass than soil or pulp mill sludge but will still be adequate if applied at a minimum rate of 3900 g m^{-2} (39 Mg ha^{-1}) for manure and 4500 g m^{-2} (45 Mg ha^{-1}) for wood shavings amendment. Hay and straw did not satisfactorily ameliorate the limestone substrate.

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