Sustainability **2013**, *5*, 1340-1355; doi:10.3390/su5031340

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Increasing Woody Species Diversity for Sustainable Limestone Quarry Reclamation in Canada

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Received: 31 December 2012; in revised form: 17 February 2013 / Accepted: 21 February 2013 / Published: 20 March 2013

Abstract: Environmental sustainability of post mined limestone quarries often requires reclamation to a diverse woody plant community. Woody species diversity may be severely limited if only nursery stock is relied on for propagation material; thus other sources must be evaluated. To address woody species establishment and survival from different propagule sources at a limestone quarry in western Canada, native trees (4) and shrubs (3) were seeded and transplanted into amended substrates (wood shavings, clean fill, unamended control) in two seasons (spring, fall). Plant sources were nursery stock, local forest wildlings, seeds and forest soil (LFH mineral soil mix). Plant emergence, survival, height, health and browsing were evaluated over four years. Survival was greater with fall transplanted seedlings than with spring transplanted. Survival was greater for *Picea glauca, Pseudotsuga menziesii* and *Populus tremuloides* from nursery than local source stock. Seedlings from seeds and LFH did not survive for any of the species. Growth and survival were affected by bighorn sheep. Amendments did not improve plant establishment. Diversity of the woody plant community was increased at the quarry in spite of the severe conditions.

Keywords: woody vegetation; nursery stock; local wildlings; seeds; LFH mineral soil mix; spring planting; fall planting; limestone quarry; reclamation; bighorn sheep

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1. Introduction

Quarries are often located in ecologically sensitive areas where their large disturbances contribute to habitat fragmentation and loss of interior forest species' habitat and diversity from edge effects [1,2]. These disturbances result from removing vegetation and soil, drilling and blasting to reach the mineral ore. The open cut method is most often used for limestone extraction and increasingly used for other minerals because it facilitates more complete and economic extraction [3]. The ability to reclaim these mines to a specified, sustainable end land use relies on development of the science and techniques for reestablishment of ecosystem function.

Sustainable mining involves social, economic, technological and environmental factors [3]. In Canada, mining companies have played a prominent leadership role integrating sustainability into their policies and practices [4], understanding that environmental management and effective planning for mine closure are challenges to be addressed by the mining sector [5]. Mine reclamation contributes to sustainability, allowing mining to be a transitional phase to another sustainable state.

The Global Reporting Initiative [6] suggests that biodiversity should be considered among the environmental factors for mining sustainability. Effective reclamation practices leading to re-establishing processes and biodiversity are critical. The ability of a community to maintain many ecological services has been linked to high biodiversity and species richness [7,8]. Quarries are located in a variety of environments and reclamation approaches must often be adjusted to these environment types. Thus development of reclamation strategies for specific environments becomes important. Results can be extrapolated to other quarries and disturbance types with similar conditions increasing sustainability of productive activities in the region.

More than 40 years of reclamation practices in subalpine and montane ecosystems of Alberta have shown that two of the most critical elements for reclamation success are selection of native species and soil management [9,10]. When salvaged topsoil is not available, anthroposols can be constructed in a cost effective manner. Anthroposols are azonal soils that have been highly modified or constructed by human activity after disturbances [11]. Anthroposols have been successfully utilized in reclamation projects around the world, including Europe [12] and Canada. Limestone waste rock and overburden have been used successfully to construct anthroposols where vegetation can establish and has potential to address absent or limited top soil availability at limestone quarries [13]. These anthroposols were developed at the Exshaw quarry in the Canadian Rocky Mountains, increasing establishment of grasses and forbs [14].

Although assisted revegetation may not always be needed or desired during reclamation [15], in the province of Alberta and many other jurisdictions, provincial and federal authorities mandate which grass and tree species must be included in the quarry reclamation plan. A plant community that includes woody vegetation is desired and legally required at the Exshaw quarry for reestablishment of natural habitat and ecological services. Even though limited guidelines are available on how to develop natural habitats, decisions for a target vegetation community can be partially based on characteristics, land use and protection status of adjacent areas [16]. The Exshaw quarry is surrounded by montane-subalpine forest. Although desirable, establishing woody vegetation on highly disturbed land is challenging. Natural establishment may be very slow, taking years for individual plants to reach their reproductive stage; seedlings commonly have low survival rates. Although natural forest regeneration and enrichment of floristic composition could occur if undisturbed forest or other plant community fragments near the disturbed area become a source for seeds, propagules and seed dispersers [17,18], human assisted revegetation is required for more rapid development of a diverse community. Substrate in the reclaimed area was established by deposition and recontouring of quarry waste material, with negligible organic matter and nutrients, extremely poor water retention and soil structure and very high pH. These substrates make the likelihood of unassisted establishment of native species very low, and increase the risk of colonization by invasive species, as supported by the extremely low vegetation cover on the site prior the experiment.

Plant species selected to revegetate a limestone quarry should survive and grow under conditions of rocky substrates, low soil nutrients and water content, high soil pH and steep slopes of various aspects. At latitudes where the growing season is short, transplanting and seeding season may greatly affect plant survival. Plants introduced in spring may establish quickly, taking advantage of an increasingly longer photoperiod over summer, but they are at risk of overheating and desiccation. Plants introduced in fall will likely go dormant and delay growing until the next spring when they will rely on carbohydrate reserves to start growing. Tolerance to environmental conditions related to season of planting may vary with species. Thus reclamation strategies to increase plant survival are important.

Use of a variety of native species in revegetation helps to retain biodiversity on a reclaimed area [1,19] as species will contribute differently to the community. A variety of deciduous and evergreen trees and shrubs should be used to approximate undisturbed conditions in a mountain forest ecoregion to build functional diversity of the community. Positive effects of shrubs on tree establishment [20,21] and nitrogen fixing plants on their neighbors [22,23], are well documented. Use of local ecotypes and cultivars in revegetation may increase survival and fitness [24,25]. Transplanting trees and shrubs are most likely to speed up natural succession, reducing the time for secondary forest vegetation establishment. Seeding may be a less expensive way to introduce woody species although establishment from seeds is often low. Use of donor soils as a source of native plant propagules for revegetation is an innovative technique that has proven successful in the environments and disturbances where it has been tested [26,27]. Forest floor material containing litter (L), fermented and fragmented litter (F) and humus (H) mixed with parts of the upper soil horizon (LFH mineral soil mix, has high concentrations of viable propagules from a variety of species for which seed cannot be collected or purchased [27].

The research discussed in this paper emerged from a series of experiments at the Exshaw limestone quarry in the Canadian Rocky Mountains where soil, vegetation and nutrient cycling were considered critical components to be reintroduced for reestablishment of ecosystem function. Anthroposols were constructed with limestone substrates and tested using grasses and forbs and microbiota was assessed [11,14]. Specifically, this research was designed to assess limestone quarry reclamation potential of select species of native trees and shrubs; to determine whether plant material source (nursery, local transplants from quarry locations, local LFH mineral soil mix, seeds), planting and seeding season and soil amendments (fertilized clean fill, wood shavings) would affect woody species survival towards successful establishment of a diverse woody plant community.

2. Results and Discussion

2.1. Survival and Growth of Out Planted Trees and Shrubs

Survival of out planted species was significantly affected by transplanting season ($p < 0.001$). After four growing seasons, survival was highest for individuals out planted in fall than in spring (Table 1). These differences were evident from the first assessment date and persisted to the end of the experiment. Individual species responded differently to season of transplanting and time since transplanting. Planting season affected *Picea glauca* (white spruce) local ($p < 0.001$), *Picea glauca* nursery ($p < 0.001$), *Populus tremuloides* (trembling aspen) ($p < 0.003$) and *Pseudotusga menziesii* (douglas fir) ($p < 0.003$) the year of planting. After four years, only *Picea glauca* local and *Betula papyrifera* (paper birch) showed significant differences due to planting season (Tables 1 and 2). Survival of *Populus tremuloides*, *Pseudotsuga menziesii* and *Picea glauca* (nursery) although lower when spring planted, were higher than the other species (Figure 1 and Table 1). Twice as many plants of *Betula papyrifera* and *Picea glauca* (local) survived fall planting. *Juniperus horizontalis* (creeping juniper) survival was low regardless of planting season.

Table 1. Number of surviving plants with spring (S) and fall (F) planting over four growing seasons.

	2007		**2008**				**2009**				**2010**	
	October		**May**		**August**		**May**		**August**		**August**	
Species	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**
Betula papyrifera	21	26	18	25	18	24	12	24	10	23	10 b	18 a
Juniperus horizontalis	3	6	2	2	1	2	1	2	1	2	1	2
Picea glauca (local)	13 b	27 a	12	26	12	24	12	23	11	23	11 b	22 a
Picea glauca (nursery)	17 b	30 a	17	27	17	24	17	23	17	23	17	23
Populus tremuloides	21 b	29 a	20	29	19	26	19	23	19	22	19	22
Pseudotsuga menziesii	16 b	29 a	16	25	16	25	16	25	16	25	15	25

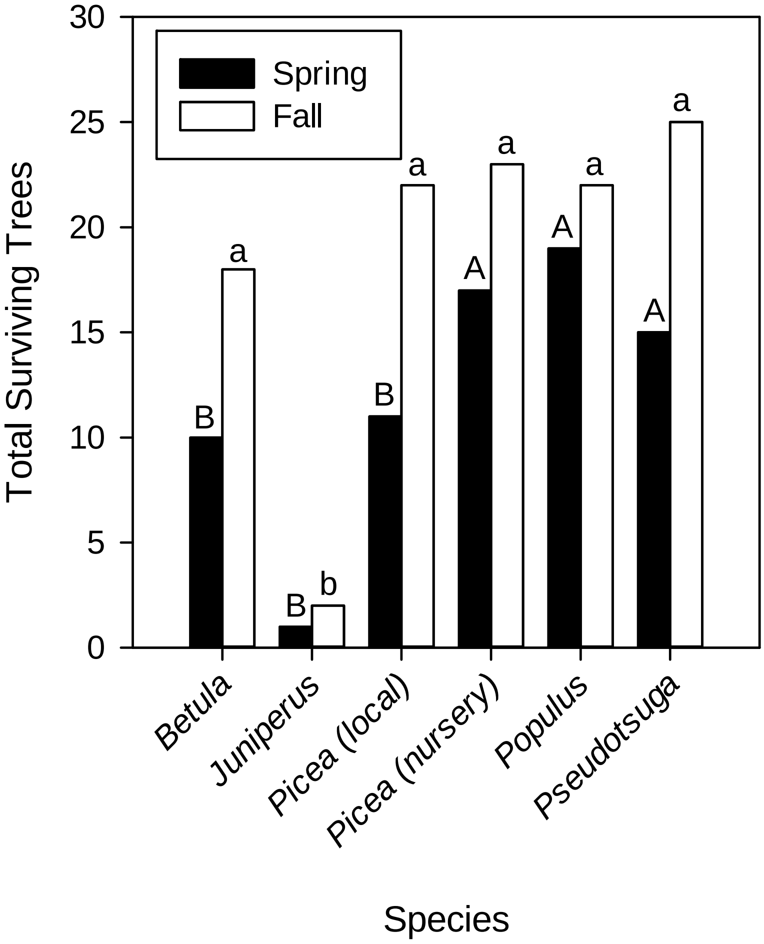
There were 30 initial transplants per treatment. Different letters indicate significant differences in survival between spring and fall planting of the same species. Data were statistically analyzed for 2007 and 2010.

Table 2. Residuals and Akaike information criterion values (AIC) from logistic regression of survival data of trees planted in spring and fall.

		Spring		**Fall**	
Monitoring Dates	**Explanatory Variable**	**Residual Deviance**	**AIC**	**Residual Deviance**	**AIC**
October 2007	Species	206.7	218.0	90.6	104.6
May 2008		214.4	226.4	120.4	134.4
August 2008		209.8	221.8	152.0	166.0
May 2009		206.7	218.7	166.5	180.5
August 2009		206.6	218.6	171.3	185.3
August 2010		206.7	218.7	181.3	195.3
October 2007	Soil treatment	248.0	254.0	170.8	176.8
May 2008		247.6	253.6	204.5	210.5
August 2008		247.1	253.1	220.2	226.2
May 2009		244.3	250.3	226.7	232.7
August 2009		242.3	248.3	229.9	235.9
August 2010		241.8	247.8	236.1	242.1

Fall treatments have smaller AIC values, closer to true expected values of complete survival.

Figure 1. Total number of surviving trees four years after transplanting. Different letters indicate significant differences among species survival with spring planting (upper case) and fall planting (lower case); n = 30.



Lower survival of spring than fall transplanted seedlings may be associated with high planting shock due to water stress. Fall planted species had some time to adjust prior to dormancy and would be better able to use early spring water from snow melt. Seedlings expend more energy for respiration under warmer temperatures [28] and increasing temperatures over summer could reduce soil water content and further affect seedling survival [29]. Although mean air temperatures were similar during spring and fall planting in 2007 water gradients may have imposed different challenges to plant establishment. Spring planting in June occurred just before approximately 90 mm of rain in 4 days, after which rain was absent until end of the month (12 mm) [30]. Higher temperatures may have increased plant respiration and water stress. This together with browsing during summer may explain the higher mortality rates with spring planting. Further stress to spring planted individuals could have been induced by low fall air temperatures and short photoperiods limiting photosynthesis and thus reserve accumulation, both key physiological processes to plant survival over winter.

Highest mortality for most species occurred during the first months after planting, especially spring plantings (Table 3). *Juniperus horizontalis* had highest mortality and *Populus tremuloides* lowest. Although *Betula papyrifera* mortality was lowest immediately after planting, it had higher consistent mortality over time and second highest mortality at the end of the experiment. Lowest mortality occurred with fall planting, and after four years ranged from 17–40% depending on tree species (Table 3). Mortality may increase in the following years. Highest mortality early in the revegetation period is common as many plants do not adjust to their new surroundings and experience high transplant shock. However, some studies show a decline in survival even after long periods of time. For example, in one study in New Mexico, survival dropped from 80% in the first 3 years to 43% by year 12 although most plant deaths occurred within the first 9 years [31].

Table 3. Mortality (%) of trees with spring (S) and fall (F) planting relative to the previous assessment date.

	2007		**2008**				**2009**				**2010**			
	October		**May**		**August**		**May**		**August**		**August**		**Final**	
Species	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**	**S**	**F**
Betula papyrifera	30	13	10	3	0	3	20	0	7	3	0	17	67	40
Juniperus horizontalis	90	80	3	13	3	0	0	0	0	0	0	0	97	93
Picea glauca (local)	57	10	3	3	0	7	0	3	3	0	0	3	63	27
Picea glauca (nursery)	43	0	0	10	0	10	0	3	0	0	0	0	43	23
Populus tremuloides	30	3	3	0	3	10	0	10	0	3	0	0	37	27
Pseudotsuga menziesii	47	3	0	13	0	0	0	0	0	0	3	0	50	17

Picea glauca and *Pseudotsuga menziesii* nursery stock had higher survival than local sourced material, particularly if planted in spring. Nursery stock had well developed root systems relative to local collected stock, which likely reduced water stress. High mortality of *Juniperus horizontalis* occurred, likely due to root system damage during extraction from natural areas. Extraction with relatively intact root systems was difficult due to substrate characteristics and the extensive root system, sometimes shared with a parental plant.

Soil treatments had no significant effect on plant survival (Table 2). Clean fill and wood shavings did not affect substrate function and structure as anticipated, likely because controls were physically improved during soil preparation prior to transplanting. While preparing the planting hole, large rocks and pebbles were removed. Once transplants were placed, holes were filled with substrate which was similar to clean fill. Wood shavings had improved substrate properties, including water retention, in a greenhouse experiment with limestone substrates [11], although in the field wood shavings did not improve woody species survival. Thus other amendments should be studied with woody species transplanting, such as pulp mill biosolids, aiming to increase soil nutrients and water content and reduce bulk density. Our amendments improved soil physical and chemical properties, including water retention, but were not associated with increased soil heterogeneity which was limited by the overall harsh chemical (e.g., high pH), environmental (e.g., low temperatures and precipitation) and ecological (e.g., herbivory) conditions.

Success in planting includes survival and growth [32]. Depending on species, 38–60% of planted trees increased in height during the four years of the experiment, with greater increases for fall than spring planted trees. Trees that survived to the end of the experiment had 2 to 6 cm height increases over the four years (Table 4). The few plants that consistently increased in height over two consecutive assessment dates appeared to do so by escaping browsing. Poor height increase for all stock types can be associated with dry sites resulting from southern aspects and coarse parent material leading to limited soil water and nutrients, high sun exposure, extreme temperatures, slope and rocky substrate.

Other studies have shown that water stress decreases bud production, which may affect following year growth [33].

Table 4. Live trees four years after transplanting with increased height at any given time interval between assessment dates (2007–2010).

Planting Season	Species	Number of Survivors	Number with Height Increase	% Trees with Increased Height	Mean Height Increase (cm)	Range of Increase from Individual Plants (cm)
Spring	*Betula papyrifera*	10	4	40	2.9	1–5
	Juniperus horizontalis	1	1	100	2.2	1.5–3
	Picea glauca (local)	11	10	91	4.2	1–9
	Picea glauca (nursery)	17	14	82	4.4	1–17
	Populus tremuloides	19	9	47	4.8	1–10.5
	Pseudotsuga menziesii	15	11	73	2.1	1–6
Fall	*Betula papyrifera*	18	6	33	6.5	1–16
	Juniperus horizontalis	2	2	100	5.3	4–6
	Picea glauca (local)	22	20	91	4.5	1–10
	Picea glauca (nursery)	23	14	61	3.1	1–13
	Populus tremuloides	22	9	44	2.8	1–8
	Pseudotsuga menziesii	25	15	60	2.5	1–9

Picea glauca had a mean height increment of 3.0–4.5 cm, with some individuals growing as much as 17 cm after three growing seasons. Vyse [34] also found plantations had two seasons of slow height increases before accelerated growth sometimes lasting three years. In this period, annual growth rarely exceeded 8 cm for *Picea glauca* and decreased in the second year for some stock types. Low height increase has been observed in other species in overburden. A 4–7 year establishment period was needed before *Pinus ponderosa* P. & C. Lawson (ponderosa pine) trees planted on overburden reached appreciable height. It may take many years (19 at the ponderosa pine plantation) for trees on overburden to achieve growing rates similar to those of the same species at undisturbed sites [35].

Evidence of browsing was observed on every assessment date, contributing to or causing plant mortality. Browsing and trampling caused more mortality to *Populus tremuloides* and *Betula papyrifera* than to *Picea glauca* or *Pseudotsuga menziesii*. During the first month after planting 44% of *Betula papyrifera* and *Populus tremuloides* deaths with spring planting and 100% of deaths with fall planting of *Betula papyrifera* and *Pseudotsuga menziesii* were attributed to bighorn sheep trampling and/or browsing. Numerous sheep and lambs were observed on site in June. The roots of the newly planted seedlings in spring treatments may not have been established well enough to endure browsing and numerous seedlings were uprooted. Seasonal migration patterns of bighorn sheep has been observed in the south eastern slopes of the Rocky Mountains. Less grazing likely occurs at the study site in fall as sheep may migrate during rut season and to winter grounds [36,37]. Large proportions of deaths of *Betula papyrifera*, *Picea glauca* (local), *Populus tremuloides* and *Pseudotsuga menziesii*, were attributed to bighorn sheep the following year. Herbivory combined with drought reduces photosynthetic tissue and lowers root reserves accumulation [38] and has had a huge impact on seedling survival in other studies [39].

Diverse communities are more resistant and resilient to perturbation, and efforts to restore entire ecological communities or ecosystems are becoming more common [40]. A mixed stand of woody species is preferable to a single stand and therefore, all the species assessed in this research could be considered for planting, except *Juniperus horizontalis* unless a source other than local transplants is found. Animal use and browsing is a part of the system and may require incorporating species that will be browsed in revegetation such as *Betula papyrifera*, *Amelanchier alnifolia* Nutt. and *Salix* spp. [36,41]. By attracting browsers, these species may spare other species susceptible to browsing damage. Management, such as use of a herbivore deterrent, could be effective to improve plant survival and growth. For example, overall increment in plant height was higher in the 2009 growing season, the last season when chemical deterrent was applied, than in the 2010 growing season, when no deterrent was used. Lower herbivore damage occurred when chemical deterrent was applied.

2.2. Plant Establishment from Seeds

The extremely low emergence of all seeded species did not allow for statistical testing of treatment effects. The dry, hot, exposed site conditions and frequent trampling by bighorn sheep caused pebbles to fall and partly or completely cover most of the seeded holes. Of the 9 seedlings that emerged, 6 were seeded in fall and 3 in spring: *Pseudotsuga menziesii* (n = 4, 3 fall, 1 spring), *Betula papyrifera* (n = 1, fall), *Arctostaphylos uva-ursi* (bear berry) (n = 1, fall), *Alnus crispa* (green alder) (n = 1, spring), unidentified propagule from LFH mineral soil mix (n = 2, 1 fall, 1 spring). In October 2007, 5 months after spring seeding, a *Betula papyrifera* seedling emerged but did not survive to spring. Most seedlings emerged in 2008 (*Pseudotsuga menziesii* n = 4); one seedling survived to the end of 2009 but died by 2010. In 2008 an *Alnus crispa* seedling emerged. An *Arctostaphylos uva-ursi* seedling emerged in May 2009 but died during summer. Propagules from LFH mineral soil mix emerged in October 2007 and May 2009 but did not survive. No plants emerged in wood shavings amended soil and no emergence occurred in 2010.

Lack of woody plant establishment from seed is likely due to extreme temperatures and low water availability at the site and trampling by bighorn sheep. Most seeding holes were partially covered with rock at every assessment date. Of the nine seedlings established, four were *Pseudotsuga menziesii*, making it the most successful species to establish from seed. Three established seedlings were fall seeded and emerged after winter, likely due to cold stratification as it is known that seeds from many woody species including *Pseudotsuga menziesii*, *Betula papyrifera* and *Picea glauca* benefit from cold stratification to germinate [24].

Germination is the most limiting stage for seeded species. Seeds must be viable and have an adequate bed to germinate. The seeding hole and surrounding substrate at the quarry had considerable bare ground. Exposed mineral soil is regarded as adequate substrate for *Picea glauca* seedling establishment, providing seeds with light and allowing for root development if water is stable [42]. However, at the quarry, rock and pebble abundance may impede seedling root growth and limit available water. Small seedlings at bare ground sites are prone to thermal stress. Seedlings above the ground, such as on a seedbed log, gain more heat than those near the ground [43]. Leaf and bud tissues elevated 5–10 cm above the soil surface can often avoid freezing stress [43]. Soil temperature can be much higher than air temperature when exposed to the sun, especially with limited available water.

Site conditions and species characteristics affect germination and seedling survival differently. In a study in the boreal forest, low temperatures limited establishment of *Picea glauca* with only 6.8% of viable seeds producing established seedlings [44]. In a study by DeLong *et al*. [42], *Picea glauca* seedling mortality was related to summer drought when water content of the upper 20–40 mm of mineral soil was reduced below wilting point. Eis [44] found greater mortality of *Picea glauca* seedlings at fully exposed dry sites in British Columbia. *Populus tremuloides* seeds are known to have low viability [44] and lower survival of *Populus tremuloides* than *Picea glauca* was found in other studies [45].

Although viability tests of seeds were not performed, some germination in the field reinforces the hypothesis that lack of establishment from seeds was due to site conditions. This was the case for LFH mineral soil mix. Despite having propagules for woody and forb species which emerged in the greenhouse (data not provided), propagules did not successfully emerge in the field. Even if more than recorded germination from LFH mineral soil mix occurred, radicles may not have been able to reach compacted horizons as occurred in a British Columbia study when at the depth of root penetration, raw humus was at wilting point a few days after rain [46]. Good plant establishment from LFH mineral soil mix at north facing slopes in the Canadian oil sands, warrants its further testing at quarry sites with different slope and aspects where more soil water may be available.

The undisturbed surrounding vegetation at the quarry may provide a source of plant propagules, for species such as *Picea glauca* and *Pseudotsuga menziesii*. *Populus tremuloides* may be intolerant to competition from other plant species [40], and should be introduced to the site during reclamation. Although *Populus tremuloides* will likely appear naturally during ecological succession, human introduction will facilitate its arrival since there are few seed sources in the mature surrounding vegetation. This was confirmed as several *Picea glauca* seedlings were observed on the site naturally established from dispersed seeds from the surrounding areas.

3. Experimental Section

3.1. Study Area

Research was conducted at the Graymont Exshaw limestone quarry near Kananaskis, Alberta, Canada (51°07'N,115°13'W). The quarry was located on a south facing slope of the Rocky Mountains below the tree line that occurs from 2,000 to 2,300 m elevation. The climate is montane-subalpine [46]. In undisturbed surrounding areas, soils are mainly brunisols with underlying calcareous parent material [46]. Reclamation research plots were established at the north west end of the Exshaw quarry at an elevation of 1,525 m on an embankment with a steep, long south facing slope approximately 75 m long, 150 m wide and with 30 degree inclination. The embankment is an engineered pile of limestone mine spoil covered with a < 10 cm layer of clean fill (admixed topsoil and subsoil). The surface was very rocky, with rocks covering approximately 70% of the area. Diameters varied from 5 cm pebbles to large rocks of 30 cm or more.

3.2. Treatments and Experimental Design

3.2.1. Experimental Design

In June 2007, a 1040 m^2 (52 × 20 m) area was divided into four 10 × 20 m sections, each separated by a 4 m buffer. Two sections were allocated to spring season and two to fall season planting, alternated to decrease effect of location. Within spring and fall treatments, plant sources and soil treatments were randomly assigned to a grid of holes excavated 1 m apart with a shovel to a standard size for transplanting and seeding. Transplant holes were 20 cm diameter × 20 cm depth; seeding and LFH mineral soil mix holes were 15 cm diameter × 10 cm depth. Individuals of each plant source were planted or seeded into three soil treatments. Every combination of soil treatment and plant source was replicated ten times. The experimental design had 2 transplanting and seeding seasons × 3 soil treatments including control × 13 plant sources × 10 replicates = 780 planting and seeding holes (Table 5).

Table 5. Season, soil amendment, plant species and plant sources treatments used at the Exshaw limestone quarry.

		Plant Sources	
Transplanting and Seeding Season	**Soil Amendment**	**Transplants**	**Seed**
Fall	Control	aspen	aspen
	Cleanfill	douglas fir	bearberry
	Woodshavings	juniper	douglas fir
		paper birch	paper birch
		spruce (local)	spruce
		spruce (nursery)	green alder
			LFH*
Spring	Control	aspen	aspen
	Cleanfill	douglas fir	bearberry
	Woodshavings	juniper	douglas fir
		paper birch	paper birch
		spruce (local)	spruce
		spruce (nursery)	green alder
			LFH *

* Locally collected LFH mineral mix as source of propagules.

3.2.2. Soil Amendments and Fertilizer

Two amendments and fertilizer were selected to improve physical and chemical properties of limestone substrate and adequate plant establishment from a previous greenhouse study [11]. Wood shavings were fine screened from pine and white spruce wood. Clean fill, consisting of subsoil excavation material, was procured from the Exshaw quarry stock piles. Wood shavings were applied at 11.25 Mg ha^{-1} and clean fill at 482 Mg ha^{-1}. Amendment treatments were prepared by hand mixing the soil excavated at each hole with a proportional amount of amendment. Slow release fertilizer (14-14-14 nitrogen, phosphorus, potassium) was applied at 1.1 Mg ha^{-1}. Both spring and fall season, all soil amendments and all plant source materials were fertilized, except LFH mineral soil mix. Due to bighorn sheep (*Ovis canadensis* Shaw 1804) browsing, Plantskydd, a biodegradable chemical deterrent, was hand sprayed according to manufacturer instructions over the research area in June 2008 and April 2009.

3.2.3. Plant Species and Sources, Transplanting and Seeding

Transplants and seeds of seven plant species and locally collected LFH mineral soil mix were used for a total of 13 plant sources (Table 5). Plant species were selected based on being native to the area and availability. Species were *Picea glauca* (Moench) Voss (white spruce), *Pseudotsuga menziesii* (Mirbel) Franco (douglas fir), *Populus tremuloides* Michx. (trembling aspen), *Betula papyrifera*

Marshall (paper birch), *Juniperus horizontalis* Moench (creeping juniper), *Alnus crispa* (Aiton.) Pursh (green alder) and *Arctostaphylos uva-ursi* (L.) Spreng. (bear berry).

Seedlings and wild collected seeds were obtained from a nursery approximately 50 km east of the study site. Species introduced both as plug transplants and seeds from the nursery were *Pseudotsuga menziesii*, *Populus tremuloides*, *Betula papyrifera* and *Picea glauca*. With the exception of *Picea glauca*, these species are fast growing, early successional and tolerant of soils with low nutrient content. These properties made them good candidates to facilitate establishment of non-woody species while jump-starting a secondary forest stand. Seeded only species were *Alnus crispa* and *Arctostaphylos uva-ursi*. Plugs were one year old stock and average height was 30 cm. Introducing plug seedlings was more expensive than seeding any species used in our experiment. Nonetheless, we were interested in determining if this planting method could balance the higher initial cost by increasing plant establishment and survival.

Local wildlings were procured from the quarry and adjacent forested areas. Local *Picea glauca* transplants were collected from the gravelly quarry compound where they established from naturally dispersed seeds. Exact age of local transplants is unknown, but they were between one to a few years old with an average height of 20 cm. *Juniperus horizontalis* was collected from adjacent forest sites, and only used if after lifting the plant from the soil it still had a large portion of roots in good condition.

LFH mineral soil mix was collected from a forest area adjacent to the experimental site with shovels from three scattered sites of 1 × 1 m to a depth of 5 cm, which included no more than 1 cm mineral soil. Material from the three sites was composited and homogenized prior to placement of a 5 cm layer in allocated holes. All plants were transplanted within 48 hours of being carried from the nursery or lifted from the local sites. One individual was transplanted per planting hole. 10 seeds of each woody species were sown. The small size *Populus tremuloides* seeds were sown 20 to a hole. *Betula papyrifera*, *Alnus crispa* and *Populus tremuloides* seeds were placed on the surface and lightly pressed into the substrate; *Arctostaphylos uva ursi*, *Pseudotsuga menziesii* and *Picea glauca* seeds were placed and covered with a very thin layer of substrate from the hole, equivalent to 1 or 2 times the seed diameter. Seeding and planting of woody species occurred in 2007; spring treatments from 14–18 June and fall treatments from 31 August to 3 September.

3.3. Vegetation Assessment

Plant survival, plant height and seedling emergence and survival were assessed and plants were evaluated for evidence of browsing or pulling out by bighorn sheep and buds presence. Assessments occurred on October 8–10, 2007; May 14–15, 2008 and 23–24, 2009 and August 14–15, 2008, 23–24, 2009 and 25, 2010.

3.4. Statistical Analyses

Plant survival data were analyzed using logistic regression. The variation explained by transplanting season, soil amendments and species to plant survival during four growing seasons was assessed by examining the change in residual deviance resulting from removing factors from the model. Model fitting for survival was done using a logit link [48,49]. The response variable was survival at each assessment date from October 2007 to August 2010 (0 = died, 1 = survived); explanatory variables were transplanting season (fall, spring), soil treatments (clean fill, wood shavings, unamended control) and transplanted species. Analysis of deviance of residuals was used to determine differences in survival due to species and amendments in fall and spring treatments. Akaike information criterion (AIC) values were used to compare how good the logit model explained survival of fall and spring treatments. AIC judges a model by how close fitted values are to true expected values, as summarized by an expected distance between the two [50]. Smaller AIC values indicate fitted values are closer to true expected values. Effect of planting season on survival of individual species was conducted by analyses of deviance and chi square statistics were used for calculation of significance of the factor. Chi square test is the most appropriate for a model with known dispersion, binomial in the case of survival data. R statistical language [51] was used for analyses; graphics were done with SigmaPlot 12 [52].

Mortality of plants was determined as time intervals among planting and assessment dates. For example, the first estimation was calculated as: % mortality = ((live transplants $_{\text{(planting date)}}$ − live transplants $_{\text{(assessment date 1)}}$)/live transplants $_{\text{(planting date)}}$) × 100. Height increments of each transplant in a growing season (May to August) and between years (August to August the following year) were calculated as the difference from a measured height minus the previous measured height of each transplant between assessment dates. Mortality and height data were summarized but not statistically analyzed. Data from seeds or LFH mineral soil mix were too limited for statistical analyses. Established seedlings at each assessment date and treatment were counted and data were summarized.

4. Conclusions

Environmental sustainability of limestone mining on forested mountains requires successful establishment of a diverse woody plant community. Survival of evergreen and deciduous trees planted at Exshaw quarry varied with species, planting season and plant source. Evergreen species had higher survival the first year after planting than deciduous and were less affected by planting season. *Pseudotsuga menziesii* and *Populus tremuloides* had highest survival. These species and *Picea glauca* (nursery) can be planted in either spring or fall. *Betula papyrifera* and *Picea glauca* (local) could have twice as many surviving plants if planted in fall. *Juniperus horizontalis* dug from the adjacent forest had low survival with either spring or fall planting. Higher mortality occurred in the first months after planting.

Browsing was more intense in summer, affecting recent spring transplants the most. Browsing and trampling caused greater mortality to *Betula papyrifera* and *Populus tremuloides* than to *Picea glauca* or *Pseudotsuga menziesii*. Height increase was limited particularly for broad leaved trees, which suffered more browsing. Bighorn sheep are part of the quarry ecosystem and animal use and browsing must be considered. The use in revegetation of a few favourites of sheep could be considered and more intense management of herbivores should be investigated. Plantskyd was successful in reducing herbivore use and could be applied on a more frequent basis over the growing season.

Nursery transplants had higher survival than local transplants taken from around the experimental site. Survival of local transplants varied with species and was significantly higher for *Picea glauca* than for *Juniperus horizontalis*, the only two species tested from local sources. Local *Picea glauca* had high survival, especially when planted in fall and will contribute to maintaining the local genetic pool. Taking naturally established plants for transplanting on the reclamation site may be destructive to undisturbed areas, and will need to be moderated; obtaining nursery transplants or allowing it to naturally disperse to the site may be more appropriate. Other tree and shrub species from natural surrounding areas should be studied for their potential use in revegetation.

Seeding woody species was unsuccessful due to the lack of seedling emergence and high mortality of the few seedlings that emerged. Exposure to desiccation, extreme temperatures and bighorn sheep trampling were the likely causes of insignificant emergence from seeds and propagules in the LFH mineral soil mix. Higher seedling establishment from these sources may be achieved in other more sheltered parts of the quarry, avoiding south facing slopes, or modifying conditions such that seedbeds with higher soil water, buffered temperatures and protection from trampling can be achieved.

Soil amendments did not significantly improve plant establishment or survival. Identifying amendments that will more effectively modify soil characteristics and result in microsites with buffered soil temperatures and increased soil water content is recommended.

Initial establishment of a woody community was achieved. Vegetation from five woody species increased biodiversity at the quarry reclamation sites with high survival of *Picea glauca*, *Pseudotsuga menziesii* and *Populus tremuloides*.

Acknowledgments

Thank you to the Mexican National Council For Science and Technology (CONACyT) for a scholarship; Graymont Company for research funding, research site and logistical support; and Bow Point Nursery for donated seeds.

Conflict of Interest

The authors declare no conflict of interest.

References

1. Martínez-Garza, C.; Howe, H.F. Restoring tropical diversity: Beating the time tax on species loss. *J. Appl. Ecol.* **2003**, *40*, 423–429.
2. Wickham, J.; Riitters, K.; Wade, T.; Coan, M.; Homer, C. The effect of Appalachian mountaintop mining on interior forest. *Landsc. Ecol.* **2007**, *22*,179–187.
3. Mudd, G.M. The environmental sustainability of mining in Australia: Key mega-trends and looming constraints. *Resour. Policy* **2010**, *35*, 98–115.
4. Costa, S.; Scoble, M. An interdisciplinary approach to integrating sustainability into mining engineering education and research. *J. Clean. Prod.* **2004**, *14*, 366–373.
5. Mining, Minerals And Sustainable Development Project (MMSD). Breaking new ground, mining, minerals and sustainable development. International Institute for Environment and Development. Earthscan Publications: London, UK, 2002. Available online: http://www.iied.org/mmsd/finalreport/index.html (accessed on 5 November 2012).
6. Global Reporting Initiative (GRI). Sustainability reporting guidelines and mining and metals sector supplement. RG version 3.0/MMSS final version. Available online: https://www.globalreporting.org/resourcelibrary/MMSS-Complete.pdf (accessed on 5 November 2012).

7. Petchey, O.; Gaston, K. Functional diversity (FD), species richness and community composition. *Ecol. Lett.* **2002**, *5*, 402–411.
8. Menninger, H.L.; Palmer, M.A. Chapter 5. Restoring Ecological Communities: From Theory to Practice. In *Foundations of Restoration Ecology*; Falk, D.A., Palmer, M.A., Zedler, J.B., Eds.; Island Press: Washington, DC, USA, 2006; pp. 88–112.
9. Lamb, T.; Naeth, M.A.; Rothwell, R. Reclamation evaluation of the Rogers Pass Project. Prepared for Parks Canada and Canadian Pacific Railway, 1998; p. 44.
10. Macyk, T.M. Thirty Years of Reclamation Research in the Alpine and Subalpine Regions near Grande Cache, Alberta. In Proceedings of the 26th Annual British Columbia Mine Reclamation Symposium; Dawson Creek, BC, Canada, 9–13 September 2002; pp. 22–33.
11. Naeth, M.A.; Archibald, H.A.; Nemirsky, C.L.; Leskiw, L.A.; Brierley, J.A.; Bock, M.D.; VandenBygaart, A.J.; Chanasyk, D.S. Proposed classification for human modified soils in Canada: Anthroposolic order. *Can. J. Soil. Sci.* **2012**, *92*, 7–18.
12. Čermák, P. Forest reclamation of dumpsites of coal combustion by-products (CCB). *J. For. Sci.* **2008**, *54*, 273–280.
13. Cohen-Fernández, A.C.; Naeth, M.A. Anthroposol development from limestone quarry substrates. *Can. J. Soil. Sci.* **2013**, submitted for publication.
14. Cohen-Fernández, A.C.; Naeth, M.A. Erosion control blankets, organic amendments and site variability influenced the initial plant community at a limestone quarry in the Canadian rocky mountains. *Biogeosciences Discuss* **2013**, *10*, 3009–3037.
15. Solondz, D.M. Improving Rehabilitation Options through Research. In Proceedings of the Mining and Environment V Conference, Sudbury, Canada, 25–30 June 2011.
16. Shulz, F.; Wiegleb, G. Development options of natural habitats in a post-mining landscape. *Land Degrad. Dev.* **2000**, *11*, 99–110.
17. Wunderle, J.M., Jr. The role of animal seed dispersal in accelerating native forest regeneration on degraded tropical lands. *For. Ecol. Manage* **1997**, *99*, 223–235.
18. Rodrigues, R.R.; Martins, S.V.; de Barros, L.C. Tropical rain forest regeneration in an area degraded by mining in Mato Grosso State, Brazil. *For. Ecol. Manage* **2004**, *190*, 323–333.
19. Gerling, H.S.; Willoughby, M.G.; Schoepf, A.; Tannas, K.E.; Tannas, C.A. *A Guide to Using Native Plants on Disturbed Lands*; Alberta Agriculture, Food and Rural Development: Edmonton, AB, Canada, 1996.
20. Callaway, R.M.; Davis, F.W. Recruitment of *Quercus. agrifolia* in central California: The importance of shrub-dominated patches. *J. Veg. Sci.* **1998**, *9*, 647–656.
21. Rousset, O.; Lepart, J. Shrub facilitation of *Quercus. humilis* regeneration in succession on calcareous grasslands. *J. Veg. Sci.* **1999**, *10*, 493–502.
22. Del Moral, R.; Wood, D.M. Early primary succession on the volcano Mount St. Helens. *J. Veg. Sci.* **1993**, *4*, 223–234.
23. Gomez-Aparicio, L. The role of plant interactions in the restoration of degraded ecosystems: A meta-analysis across life-forms and ecosystems. *J. Ecol.* **2009**, *97*, 1202–1214.
24. Campbell, R.K.; Sorensen, F.C. Effect of test environment on expression of clines and on delimitation of seed zones in douglas-fir. *Theoret. Appl. Genet.* **1978**, *51*, 233–246.

25. Smith, B.M.; Diaz, A.; Winder, L.; Daniels, R. The effect of provenance on the establishment and performance of *Lotus corniculatus* L. in a re-creation environment. *Biol. Conserv.* **2005**, *125*, 37–46.
26. Holmes, P. Shrubland restoration following woody alien invasion and mining: Effects of topsoil depth, seed source, and fertilizer addition. *Restor. Ecol.* **2001**, *9*, 71–84.
27. Mackenzie, D.D.; Naeth, M.A. The role of the forest soil propagule bank in assisted natural recovery after oil sands mining. *Restor. Ecol.* **2009**, *18*, 418–427.
28. Kramer, P.J.; Kozlowski, T.T. *Physiology of Woody Plants*; Academic Press: New York, NY, USA, 1979.
29. Harrington, G.N. Effects of soil moisture on shrub seedling survival in semi-arid grassland. *Ecology* **1991**, *72*, 1138–1149.
30. Environment Canada. Banff station. Canadian climate normals 1971–2000. Available online: http://www.climate.weatheroffice.gc.ca (accessed on 18 June 2011).
31. Young, B.J.; Harrington, J.T.; Loveall, M.W.; Wagner, A.; Sanders, J.; Buchanan, B.A. Short and Long Term Transplant Performance on Mine Rock Material, Questa mine, New Mexico, National Meeting of the American Society of Mining and Reclamation, Billings, MT, USA, 30 May–5 June, 2009; Barnhisel, R.I., Ed.s; American Society of Mining and Reclamation: Lexington, KY, USA, 2009; pp. 1698–1710.
32. Johnson, P.S.; Rogers, R. A method for estimating the contribution of planted hardwoods to future stocking. *For. Sci.* **1985**, *31*, 883–891.
33. Haase, D.L.; Rose, R. Soil moisture stress induces transplant shock in stored and unstored 2 + 0 douglas-fir seedlings of varying root volumes. *For. Sci.* **1993**, *39*, 275–294.
34. Vyse, A. Growth of young spruce plantations in interior British Columbia. *For. Chron.* **1981**, *57*, 174–180.
35. Harrington, J.T.; Loveall, M.W. Evaluating Forest Productivity on Reclaimed Mine Land in Western United States. In *Proceedings of the 7th International Conference on acid rock drainage*, 26–30 March 2006; American Society of Mining and Reclamation: Lexington, Kentucky, USA, 2006; pp. 721–737.
36. McCann, L.J. Ecology of the mountain sheep. *Am. Midl. Nat.* **1956**, *56*, 297–324.
37. Shannon, N.H.; Hudson, R.J.; Brink, V.C.; Kitts, W.D. Determinants of spatial distribution of rocky mountain bighorn sheep. *J. Wildlife Manag.* **1975**, *39*, 387–401.
38. Galvez, D.A.; Landhäusser, S.M.; Tyree, M.T. Low root reserve accumulation during drought may lead to winter mortality in *Poplar* seedlings. *New Phytol.* **2013**, *198*, 139–148.
39. Cole, E.C.; Newton, M.; Youngblood, A. Regenerating white spruce, paper birch, and willow in south-central Alaska. *Can. J. For. Res.* **1999**, *29*, 993–1001.
40. Cattelino, P.J.; Noble, I.R.; Slatyer, R.O.; Kessell, S.R. Predicting the multiple pathways of plant succession. *Environ. Manag.* **1979**, *3*, 41–50.
41. Shannon, N.H.; Hudson, R.H.; Brink, V.C.; Kitts, W.D. Determinants of spatial distribution of Rocky Mountain bighorn sheep. *J. Wildl. Manage* **1975**, *39*, 387–401.
42. Steven, D.D. Experiments on mechanisms of tree establishment in old-field succession: Seedling emergence. *Ecology* **1991**, *72*, 1066–1075.

43. DeLong, H.B.; Lieffers, V.J.; Blenis, P.V. Microsite effects on first-year establishment and overwinter survival of white spruce in aspen-dominated boreal mixedwoods. *Can. J. For. Res.* **1997**, *27*, 1452–1457.
44. Eis, S. Development of white spruce and alpine fir seedlings on cut-over areas in central interior of British Columbia. *For. Chron.* **1965**, *41*, 419–431.
45. Moss, E.H. Longevity of seed and establishment of seedlings in species of *populus*. *Bot. Gaz.* **1938**, *99*, 529–542.
46. Densmore, R.V.; Page, J.C. Paper birch regeneration on scarified logged areas in southcentral Alaska. *N. J. Appl. For.* **1992**, *9*, 63–66.
47. Alberta Parks and Protected Areas Division. *Bow valley protected areas management plan, 0–7785–2221–0*; Alberta Community Development, Parks and Protected Areas: Edmonton, Canada, 2002.
48. Agresti, A. *Categorical Data Analysis*, 2nd ed.; Wiley-Interscience: New York, NY, USA, 2002.
49. Jones, O.R.; Crawley, M.J.; Pilkington, J.G.; Pemberton, J.M. Predictors of early survival in Soay sheep: cohort-, maternal- and individual-level variation. *Proc. Royal. Soc. Biol. Sci.* **2005**, *272*, 2619–2625.
50. Agresti, A. *An Introduction to Categorical Data Analysis*, 2nd ed.; Wiley-Interscience: Hoboken, NJ, USA, 2007.
51. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2011.
52. Systat Software. *SigmaPlot for Windows version 12*; Systat Software Inc.: Chicago, IL, USA, 2011.