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GROUND-BASED MECHANIZED DIRECT SEEDING IN BRITISH COLUMBIA

MANAGEMENT GUIDELINES

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MARCH 2020

ABTRACT:

The current regeneration challenges posed by salvage logging following large-scale disturbances in western Canada, such as wildfire and mountain pine beetle, warrant the need for cost-effective reforestation strategies. Mechanized ground-based direct seeding was assessed in a variety of conditions to explore viability, determine which factors influence success, and determine the expected establishment rate when seeding with B.C. tree species. This report includes guidelines and recommendations for implementing direct seeding in B.C., based on observations from operational trials established in 2013-2017 across the province.

301013565: MID-TERM FIBRE SUPPLY
TECHNICAL REPORT **TR 2020 N 33**

ACKNOWLEDGEMENTS
This project was financially supported by Natural Resources Canada under the NRCan-FPInnovations Contribution Agreement.The author would like to thank Doug Brophy and Tim Inden, Doug Brophy Contracting; Jack Lloyd, Interior SIlvi-Services; Guy Burdikin, Don Scott, and Jason Reigner, West Fraser Mills; Nicholas Plett and Blake Ford, Canfor; Bill Laing, Conifex; and Grant Glessing and Jerome Girard, Tolko Industries.

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1 BACKGROUND

Currently, approximately 80% of the harvested area in British Columbia (B.C.) is regenerated through planting (CCFM, 2019), with the remainder managed for natural regeneration. Direct seeding, and specifically ground-based mechanized direct seeding, despite operational use in other parts of the world, has not yet been widely adopted in western Canada. Most of the direct seeding research in Canada in the 1960-1980s focused on broadcast aerial seeding of jack pine and white spruce with a fixed-wing aircraft, and resulted in variable success (Waldron, 1973). Broadcast aerial seeding is still used in Ontario for jack pine and black spruce, and in Alberta to supplement natural regeneration of lodgepole pine, although the annual area treated is small (CCFM, 2019). In British Columbia, aerial direct seeding fell out of favor due to the excessive use of seed and unpredictable results.

In B.C., interest in the use of direct seeding as a regeneration option has resurfaced due to the challenges posed by large-scale disturbances, specifically the mountain pine beetle (MPB) epidemic, the increased salvage harvest levels resulting from the epidemic, and the recent catastrophic wildfire seasons. Over 1.7 million hectares within the timber harvesting land base are currently affected by remainders of the MPB epidemic and the wildfire seasons of 2017 and 2018 (Hughes, 2019). Of these, an estimated 450,000 ha was comprised of young plantations prior to disturbance, many of which may have been too young to have developed the seed bank necessary for natural regeneration.

To meet the increased demand for regeneration after such disturbance levels, it is currently forecasted that B.C. will have to accommodate a 20% increase in seedling production and planting by 2021, an increase of up to 300M seedlings from 248M in 2017 (Hughes, 2019). Current shortages in tree planting labour and related forecasted increases in wages (Robertson, 2019), logistical constraints due to the limited spring planting season, and limits to nursery capacity may force forest managers to consider alternative regeneration strategies to get the affected stands back into production.

Recent advances in ground-based mechanized direct seeding technology and better understanding of the biological requirements for germination of temperate forest conifer species have made it possible to achieve consistent results in countries like Finland, for example, where direct seeding of Scots pine makes up 20% of the annual regeneration area (Parviainen and Vastila, 2011). With ground-based mechanized direct seeding, a seeding system is mounted on a prime mover for site preparation with simultaneous automatic seeding. This has the advantage of being the cheapest proven method of direct seeding (Bryson and Van Damme, 1994), using less seed than broadcast seeding, ensuring even coverage and making use of fresh site preparation.

In collaboration with forest companies, FPInnovations followed the development of 23 ground-based mechanized direct seeding trials established in 2013-2017 (Appendix 1) in a wide variety of sites and conditions in the interior of British Columbia, with the objective of finding solutions to better implement direct seeding as a regeneration alternative in a western Canadian context.

2 DIRECT SEEDING IN CONTEXT

Direct seeding can be an attractive alternative because of the potential cost reductions when compared to tree planting. However, like with any other regeneration strategy, it is necessary to consider its advantages and disadvantages and how these relate to the forest manager's objectives for the site.

2.1 Advantages

- The initial treatment cost can be 40-60% lower than with tree planting of nursery seedlings.
- Since direct seeding can be accomplished at the same time as high-productivity site preparation treatments (e.g. disc scarification), more area can be treated in a shorter amount of time than with tree planting.
- Direct seeding is mechanized and not affected by tree planting workforce shortages or shortages in nursery seedling supply.
- Because seeds are not constrained by the same time-sensitive seasonal requirements of live seedlings, direct seeding has longer potential treatment windows. Seeding operations can make use of both shoulder seasons, and are only constrained by the ability of the site preparation equipment to get into the site.
- Forest managers have more flexibility and reduced strain on planning and logistics. There is no need for separate planning for site preparation, ordering nursery trees, and organizing and overseeing tree planting.
- Sites with high stocking requirements due to forest pests and disease can be stocked at higher densities at a low marginal cost.
- Seedlings established from seed have a more natural development of root systems that might make seedlings more resilient to biotic and abiotic disturbances.

2.2 Disadvantages

- Direct seeding presents a higher risk of regeneration failure than tree planting. This risk is tied to prolonged drought periods, which cannot be controlled or predicted.
- High numbers of seed are required to produce a sufficiently stocked site. (i.e. Ground-based mechanized direct seeding can consume 6-8x the amount of seeds used in the nursery to produce one tree.) This is an important consideration in areas where stand seed supply may be limited.
- The high number of seeds required as compared to growing nursery stock makes the use of genetically superior orchard seed economically unfeasible.
- Like with natural regeneration, final stand density and distribution are hard to control. Seeding may result in poorly stocked gaps or clumping of trees.
- Achieving consistent results is more difficult than with tree planting due to all the variables involved and the relative lack of experience.
- Not all sites are suitable for direct seeding.
- Establishing a stocked site through direct seeding takes longer than establishing a site from nursery stock, and may have implications on milestone obligations and long-term timber supply.

- Increasing regeneration delay from a seedling failure may allow competing vegetation to establish making it more difficult to establish a new stand.

3 DEVELOPING A SEEDING PRESCRIPTION

Successful reforestation from seed is dependent on site conditions, seed used (species, quality and amount), and environmental factors (

Figure 1). All elements are equally important to consider in developing a seeding prescription that ensures stocking success. Forest managers can control for the first two by developing a prescription that takes into account careful site selection, proper site preparation and good quality seed at sufficient quantities. While some environmental factors can be controlled by timing of operations, growing season precipitation remains outside of the control of the forest manager and introduces risk to the equation.

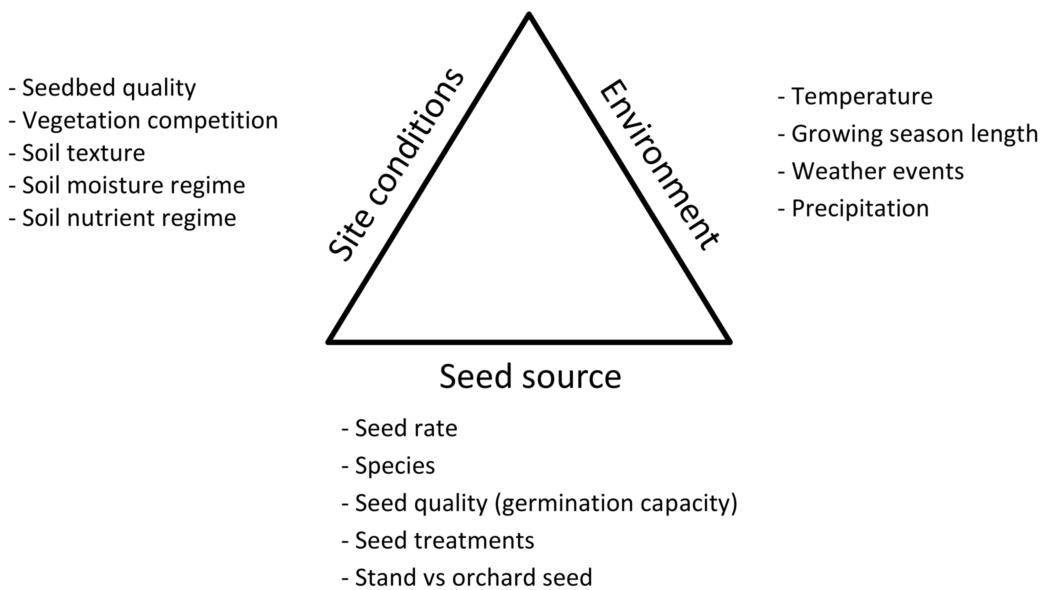

Figure 1. Successful direct seeding requires seed of adequate quality and quantity, as well as favourable site and environmental conditions.

3.1 Site selection

A direct seeding prescription starts with proper site selection that takes into account both large-scale biogeoclimatic patterns and site-specific conditions such as soil texture, moisture and nutrient regimes, vegetation competition and slash loading.

3.1.1 Biogeoclimatic subzones (BGC)

The potential of the different BGC subzones for direct seeding is outlined in the tables below, based on limiting factors to regeneration in each subzone. Several BEC zones were not considered due to factors such as: proximity to coast, extreme drought conditions, and lack of harvesting operations in the zone/subzone. A coding system is used to designate factors which may impair the success of establishment from seed, and a rating scale is used to identify the relative hazard presented by each factor (see Appendix 2). Higher scores represent a greater chance of success. The default values are based on typical pre-treatment site conditions from literature and may be adjusted to best reflect the conditions in a particular area or site. Codes are used to denote potential constraints to regeneration from seed and mitigation actions.

3.1.1.1 Interior Douglas-fir

BGC sub-zone	SMR Potential[1]	Potential constraints												Total potential
		Vegetation			Temperature Regime			Precipitation			Operability			
		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		
IDFxh	Poor			4	H	P_2, T	1	D	P_3, T	1			5	11
IDFxw	Poor			4			2			1			5	12
IDFxm	Poor			4			2			1			5	12
IDFdm	Moderate	V_3	P_1, P_2	3			4			2			5	14
IDFdk	Moderate			3			5			2			5	15
IDFmw	Good			3			3			4			5	15
IDFww	Good			3			3			5			5	16

3.1.1.2 Montane Spruce

BGC subzone	SMR Potential	Potential constraints												Total potential
		Vegetation			Temperature Regime			Precipitation			Operability			
		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		
MSxv	Marginal			5	C	P_1	1	D	T	1			4	11
MSxk	Marginal			5			3		P_3, T	1			4	13
MSdc	Good			5	C	P_1	3		T	3			4	15
MSdk	Good			5			4			4			4	17
MSdm	Good			4			5			4			4	17

[1] Soil moisture regime

3.1.1.3 Sub-boreal Spruce

BGC subzone	SMR Potential	Potential constraints												Total potential
		Vegetation			Temperature Regime			Precipitation			Operability			
		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		
SBSdh	Moderate	V_1, V_3	P_2	3	H	P_2, T	3	D	T	3			5	14
SBSdw	Good			3			4			3			5	15
SBSdk	Good			3			4			3			5	15
SBSmh	Good			4	H	P_2, T	3			4			5	16
SBSmw	Good			4			4			4			5	17
SBSmm	Good			4			5			4			5	18
SBSmk	Good			4			5			4			5	18
SBSmc	Good			4			5			4			5	18
SBSwk	Good	V_2	P_1, P_2	3			5			4			5	17
SBSvk	Good			3			5			4	N	T	3	15

3.1.1.4 Sub-boreal Pine - Spruce

BGC subzone	SMR Potential	Potential constraints												Total potential
		Vegetation			Temperature Regime			Precipitation			Operability			
		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		
SBPSxc	Moderate			4	C	P_1	3	D	T	3			5	15
SBPSdc	Moderate			4			3			4			5	16
SBPSmk	Good	V_2	P_1, P_2	3			5			5			5	18
SBPSmc	Good			3			5			5			5	18

3.1.1.5 Boreal White and Black Spruce

BGC subzone	SMR Potential	Potential constraints												Total potential
		Vegetation			Temperature Regime			Precipitation			Operability			
		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		Factor	Mitiga-tion		
BWBSdk	Good	V_3	P_1, P_2	3	C_1	P_1	4			4	N	T	3	14
BWBSmw	Good			3			5			5			3	16
BWBSwk	Good			3			4			5			3	15

3.1.1.6 Engelmann Spruce – Subalpine Fir

<table>
<tr><th rowspan="3">BGC subzone</th><th rowspan="3">SMR Potential</th><th colspan="12">Potential constraints</th><th rowspan="3">Total potential</th></tr>
<tr><th colspan="3">Vegetation</th><th colspan="3">Temperature Regime</th><th colspan="3">Precipitation</th><th colspan="3">Operability</th></tr>
<tr><th>Factor</th><th>Mitiga-tion</th><th></th><th>Factor</th><th>Mitiga-tion</th><th></th><th>Factor</th><th>Mitiga-tion</th><th></th><th>Factor</th><th>Mitiga-tion</th><th></th></tr>
<tr><td>ESSFxc</td><td>Moderate</td><td rowspan="4"></td><td rowspan="4"></td><td>5</td><td>C_2</td><td rowspan="4">P_1</td><td>1</td><td rowspan="9"></td><td rowspan="9"></td><td>4</td><td rowspan="4"></td><td rowspan="4"></td><td>4</td><td>14</td></tr>
<tr><td>ESSFdk</td><td>Moderate</td><td>5</td><td rowspan="2">C_1</td><td>3</td><td>4</td><td>4</td><td>16</td></tr>
<tr><td>ESSFdc</td><td>Moderate</td><td>5</td><td>3</td><td>4</td><td>4</td><td>16</td></tr>
<tr><td>ESSFdv</td><td>Moderate</td><td>5</td><td>C_2</td><td>1</td><td>4</td><td>4</td><td>14</td></tr>
<tr><td>ESSFmw</td><td>Good</td><td rowspan="5">V_2</td><td rowspan="11">P_1</td><td>3</td><td rowspan="2"></td><td rowspan="2"></td><td>5</td><td>5</td><td rowspan="5">S</td><td rowspan="5">T</td><td>4</td><td>17</td></tr>
<tr><td>ESSFmm</td><td>Good</td><td>3</td><td>5</td><td>5</td><td>4</td><td>17</td></tr>
<tr><td>ESSFmk</td><td>Good</td><td>3</td><td rowspan="3">C_1</td><td rowspan="3">P_1</td><td>3</td><td>5</td><td>4</td><td>15</td></tr>
<tr><td>ESSFmc</td><td>Good</td><td>3</td><td>3</td><td>5</td><td>4</td><td>15</td></tr>
<tr><td>ESSFmv</td><td>Good</td><td>3</td><td>1</td><td>5</td><td>4</td><td>13</td></tr>
<tr><td>ESSFwm</td><td>Good</td><td rowspan="6">V_1, V_2</td><td>1</td><td></td><td></td><td>4</td><td rowspan="6">W</td><td rowspan="6">P_1</td><td>3</td><td rowspan="6">S, N</td><td rowspan="6">T</td><td>2</td><td>10</td></tr>
<tr><td>ESSFwk</td><td>Good</td><td>1</td><td rowspan="5">C_1</td><td rowspan="5">P_1</td><td>3</td><td>3</td><td>2</td><td>9</td></tr>
<tr><td>ESSFwc</td><td>Good</td><td>1</td><td>1</td><td>3</td><td>2</td><td>7</td></tr>
<tr><td>ESSFwv</td><td>Good</td><td>1</td><td>1</td><td>3</td><td>2</td><td>7</td></tr>
<tr><td>ESSFvc</td><td>Good</td><td>1</td><td>1</td><td>3</td><td>2</td><td>7</td></tr>
<tr><td>ESSFvv</td><td>Good</td><td>1</td><td>1</td><td>3</td><td>2</td><td>7</td></tr>
</table>

3.1.1.7 Interior Cedar-Hemlock

<table>
<tr><th rowspan="3">BGC subzone</th><th rowspan="3">SMR Potential</th><th colspan="12">Potential constraints</th><th rowspan="3">Total potential</th></tr>
<tr><th colspan="3">Vegetation</th><th colspan="3">Temperature Regime</th><th colspan="3">Precipitation</th><th colspan="3">Operability</th></tr>
<tr><th>Factor</th><th>Mitiga-tion</th><th></th><th>Factor</th><th>Mitiga-tion</th><th></th><th>Factor</th><th>Mitigating action</th><th></th><th>Factor</th><th>Mitiga-tion</th><th></th></tr>
<tr><td>ICHxw</td><td>Moderate</td><td rowspan="3"></td><td rowspan="3"></td><td>5</td><td rowspan="6"></td><td rowspan="6"></td><td>5</td><td>D</td><td>T, P_3</td><td>3</td><td rowspan="4"></td><td rowspan="7"></td><td>4</td><td>17</td></tr>
<tr><td>ICHdw</td><td>Good</td><td>5</td><td>5</td><td rowspan="7"></td><td rowspan="7"></td><td>4</td><td>4</td><td>18</td></tr>
<tr><td>ICHdk</td><td>Good</td><td>5</td><td>5</td><td>4</td><td>4</td><td>18</td></tr>
<tr><td>ICHmw</td><td>Good</td><td rowspan="2">V_1, V_2</td><td rowspan="2">P_1, P_2</td><td>3</td><td>5</td><td>5</td><td>4</td><td>17</td></tr>
<tr><td>ICHmm</td><td>Good</td><td>3</td><td>5</td><td>5</td><td rowspan="3">S</td><td>4</td><td>17</td></tr>
<tr><td>ICHmk</td><td>Good</td><td rowspan="2"></td><td rowspan="2"></td><td>4</td><td>5</td><td>5</td><td>4</td><td>18</td></tr>
<tr><td>ICHmc</td><td>Good</td><td>4</td><td>C</td><td>P_1</td><td>3</td><td>5</td><td>4</td><td>16</td></tr>
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<tr><td>ICHvk</td><td>Good</td><td>1</td><td>4</td><td rowspan="2">W</td><td rowspan="2">P_1</td><td>2</td><td>2</td><td>9</td></tr>
<tr><td>ICHvc</td><td>Good</td><td>1</td><td>C</td><td>P_1</td><td>3</td><td>2</td><td>2</td><td>8</td></tr>
</table>

3.1.2 Site conditions

General site conditions favourable to direct seeding vary depending on larger biogeoclimatic patterns as well as site-specific factors such as topography, soil texture, and site nutrient regimes. For example, a south-facing site in the IDFdk BGC zone will likely be too hot and dry to establish from seed, compared to a north-facing IDFdk site. The contrary can be said for a MSxv site, where warmer south-facing slopes may regenerate more easily. As a general guideline, a site in an area that has been traditionally managed for natural regeneration, but where adequate cone supply and quality may be lacking, is a likely candidate for direct seeding. Sites with medium-coarse loamy soils, mesic moisture regimes, and medium-poor nutrient regimes are better suited to direct seeding as they provide adequate water supply and drainage (Figure 3), are less prone to frost heaving than fine textured soils (Figure 2), and generally have less vegetation competition than richer moisture- and nutrient-receiving sites.

Figure 2. Frost heaving damage on fine silty soils.

Figure 3. Sand textured soil showing the effect of moisture (as a result of trench aspect and shading) on germination. Right side had a southern exposure and drained too quickly to support germination.

Vegetation competition, in particular underground competition for moisture from grasses, is more of a concern when seeding than when planting, as grass tends to form thick mats of fibrous roots that can severely limit soil moisture supply to germinants (Alexander, 1974). Low to moderate shading from shrubs however can be beneficial by providing shade while not competing for light or moisture at the same extent as grasses and forbs. Shading reduces moisture stress, heat injury and may reduce frost damage by reducing loss of radiant energy from soil and seedlings (Stuart et al. 1989, Alexander, 1974).

Figure 4. Site with heavy grass competition. None of the flagged seedlings survived the first growing season.

Figure 5. Competition from shrubs such as mountain alder is not detrimental and may provide better germinant establishment conditions.

Operational constraints for site preparation, such as sensitive soils, steep slopes, or areas too wet for disc scarification, must also be taken into account when selecting sites for direct seeding. Sites that require elevated planting spots such as mounding are not suitable for direct seeding due to cold, wet soils and vegetation competition.

3.1.3 Microsite requirements

A seedbed suitable for pine germination is comprised of fresh disturbed mineral soil, due to the higher capillary action and the degree to which seed is in contact with soil moisture (Armit, 1966; Brown, 1973; Chrosciewicz, 1990). To a lesser extent, a thin humus layer of no more than 2 cm, or a mix of humus and mineral soil are also considered suitable (Chrosciewicz, 1990). During germination assessments at the trial sites, most germinants were found growing on mineral soil, with little germination observed on trench failures where the litter layer was not properly disturbed due to the presence of debris or stumps (Appendix 1).

Adequate seedbed exposure is dependent on site conditions that may reduce machine trafficability and by extension site preparation quality, such as large volumes of logging waste or large stumps. Trial data (Appendix 1) shows that seedbed quality in the disc scarified rows, as measured by the percent exposure of mineral or humus/mineral soil mixes, decreases as the amount of slash volume increases (Figure 6). In trial sites with high slash loads (300 m3/ha), seedbed quality was as low as 67%, representing a 33% reduction in effective scarification area and potential stocking (Table 1). In one trial, two study units on the same block and with the same site conditions but different slash levels (236 m3/ha vs 136 m3/ha) were seeded. One year after seeding, the high slash site had less than half the stocking of the low slash site likely due to the reduced seedbed quality (Appendix 1).

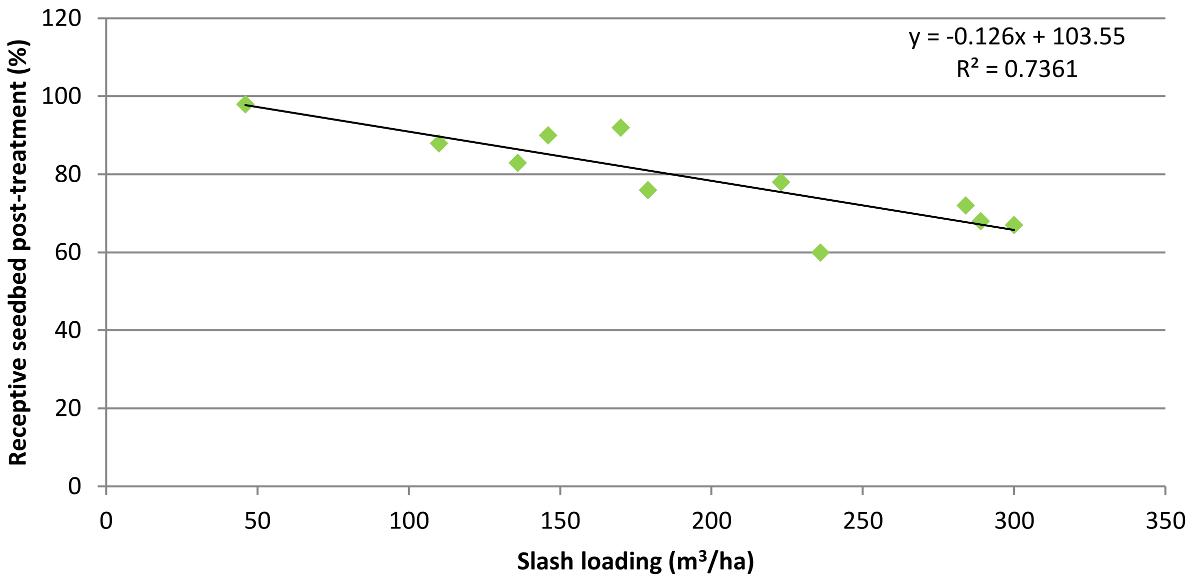
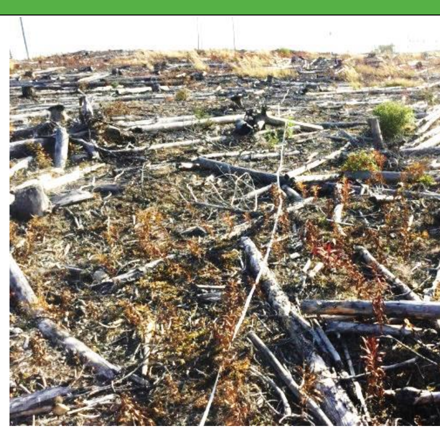


Figure 6. Relationship between slash loading and resulting seedbed quality for direct seeding.

Table 1. Site slash volume and resulting seedbed quality after disc scarification

Low slash loading	Moderate slash loading	High slash loading
		
Slash volume (m^3/ha)		
50-130	130-215	215-300
Expected seedbed quality after disc scarification (%)		
87-97	76-87	66-76

3.1.4 Regeneration delay

Another aspect of site selection that must be considered is the deadline of a given site for reaching its regeneration delay and free growing milestones. Because of the increased dependence on growing season precipitation for germination and establishment of direct-seeded sites, there is a much higher risk of regeneration failure compared to tree planting. Waiting for stocking to fully express itself, and fill-planting or replanting if it doesn't, may delay stocking of the site by 3+ years. Even in the trial with best establishment rates, it took three years to get a fully stocked site with 8 cm average height (Figure 7), whereas a planted site can be classified as satisfactorily stocked right after planting (Figure 8). The increased risk and time required to stock a site makes direct seeding an unviable option for sites with short regeneration delay timelines, or sites with constraints such as potential vegetation competition development or growing season frost issues.

Figure 7. Direct seeded seedlings after the third growing season

Figure 8. Freshly planted 2+0 410 nursery seedling

3.2 The seed

3.2.1 Species

Lodgepole pine, as one of the most easily established and commercially important tree species in B.C., has been the primary target for direct seeding efforts to date. Establishment rates[2] of up to 48% by year 3 have been observed in receptive sites with no drought events (Appendix 1), proving that lodgepole pine can be regenerated by direct seeding when conditions are right.

In our trials, establishment of interior spruce has been near null regardless of seed rates used, and therefore we cannot recommend direct seeding for regenerating interior spruce. These results are consistent with the literature, where past efforts required large amounts of seed to reach full stocking. In Ontario, aerial seeding of black spruce in lowland peatlands is common practice but requires seed rates of upwards of 100,000 seeds/ha (Adams et al, 2005). A review of 11 white spruce seeding trials by Greene & Johnson (1998) found a mean

[2] Establishment rate is defined as the ratio of number of seedlings established per number of seed sown.

establishment of 8.2% for white spruce. While site factors may have been the most influential (spruce sites tend to be richer and wetter) in the low establishment rates of spruce in our study sites, the small seed size may have been a factor as well, as larger seeds hold a higher initial energy reserve that seedlings can access to survive their most vulnerable phase (Leishman & Westoby, 1994; St-Denis et al, 2013).

Douglas-fir and western larch have been used in direct seeding trials, and though some germination and establishment has been observed, results are preliminary and the trial sites severely affected by drought shortly after seeding. There are also operational constraints when seeding with Douglas-fir in particular, as the seed is resinous and highly irregular in shape and tends to cause frequent jams in the seeding mechanism (Figure 9).

Figure 9. Lodgepole pine (Pli), interior spruce (Sx), interior Douglas-fir (Fdi), and western larch (Lw) seed.

3.2.2 Seed pretreatment

Seed pretreatment encompasses a series of processes performed at the seed storage facility to prepare seeds for sowing. Cold stratification is of particular interest for direct seeding operations planned for the spring. For many temperate conifer species, a period of cold and wet stratification helps break seed embryo dormancy and induce germination. In nature, and when seeding in the fall, this is achieved by overwintering under snow. While some lodgepole pine seed can germinate without undergoing stratification, the treatment will improve the speed and uniformity of germination, and increase seed vigour or their ability to germinate in a wider range of conditions (Kolotelo et al. 2001).

Stratification can be performed artificially upon request at the seed storage facility where the seed is sourced from. It involves soaking the seed request until moisture content reaches 30%, draining to remove excess surface moisture, and placing the imbibed seed in a moist but aerated environment, at 2-5 °C, for a period of 3 weeks (Kolotelo et al. 2001). Stratified seed has special handling requirements, see Seed Handling section for details.

3.2.3 Seed rate selection

Seed rate, the number of seeds sown over an area, is perhaps one of the easier factors to control when developing a direct seeding prescription. When selecting a seed rate however, it's important to remember that it is not possible to compensate with higher seed rates on a site with low quality seedbed or a site that is susceptible to extreme prolonged droughts.

Seed rate selection is based on germination capacity of the seedlot, expected field establishment rate, and target total stocking. Guidelines for seed rate planning are provided in Appendices 2 and 3. Germination capacity can be obtained from the seedlot label and refers to the amount of seed germinated during laboratory germination tests under controlled optimal conditions. Target total stocking will vary with management objectives for the site, expected natural ingress and site limitations such as propensity to tree diseases or pests. Where local data on the relationship between total density and well-spaced density is lacking, a ratio of 4 trees per well-spaced tree can be used as a starting point for lodgepole pine (Bancroft, 1996). While better estimates for expected field establishment rates will result as local experience develops, lodgepole pine trials suggest second-year establishment rates ranging from 6% to 33% with an average of 14%.

Second year establishment is fairly representative of what the final site stocking from seed will be, although it's important to note that during the first 5 years stocking is highly dynamic due to delayed germination, natural ingress and mortality. Most of the direct seeded lodgepole pine seed germinates within the first two growing seasons, with some germinating in the third and small amounts germinating in the fourth (Yring, 2008). Delayed germination has been observed in both stratified and unstratified seed trials (Appendix 1).

3.3 Environmental factors

In order for a seed to germinate, it needs adequate amounts of moisture, oxygen and warm temperatures. While risk of regeneration failure can be reduced by careful site selection and using adequate seed rates, weather after seeding is largely unpredictable and uncontrollable, and can determine the success or failure of direct seeding.

3.3.1 Precipitation

Soil moisture deficits are the primary source of mortality of lodgepole pine germinants during the first year after seeding, as lodgepole pine germinants are more susceptible to drought than to temperature fluctuations (Anderson et al. 1995, Petrie et al, 2006). The main factor affecting soil moisture in clearcuts is the amount of precipitation (Smith, 1962). In direct seeding trials, periods of localized summer drought in 2014, 2015 and 2017 were the primary reason for low germination and high germinant mortality in non-satisfactorily restocked study sites. Summer drought has been more of an issue in southern interior trials, and frequency and intensity of drought periods in the region may only worsen with climate change. Container-grown stock was similarly affected by drought in some cases (Appendix 1). Because seeded trees develop more natural root systems, they might be more resilient to drought events after 2 to 3 years, compared to container-grown seedlings (Figure 10)(Little & Somes, 1964).

Figure 10. Root development of a healthy spring-seeded lodgepole pine seedling at the end of the first growing season.

3.3.2 Temperature

The temperature range at which most northern conifers can germinate is between 15 and 30 °C, with the ideal temperature being 25 °C (Petrie et al, 2016; Leadem, 1996). Cooler temperatures, of 10 °C and below, will inhibit germination and induce seed dormancy. This is relevant when scheduling seeding operations, as seeding in the fall with high moisture conditions and constant temperatures of over 15 °C for over two to three weeks can result in some seed germinating that fall, even with unstratified seed. Late season germinants are less likely to be able to harden off before winter and may suffer increased mortality from late-season frosts as a result (Lotan & Perry, 1983).

While lodgepole pine seed can withstand short bursts of temperatures up to 65-75 °C (Knap and Anderson, 1980), prolonged summer temperatures of over 35 °C can also result in increased mortality in germinating seed. (Leadem, 1996). Temperatures at ground-level in clearcuts may easily exceed this threshold, which may account in part for the losses in field germination capacity from year to year and why seed is only viable for 1-4 years after seeding (whereas seed stored in the canopy seed bank can be viable for decades). Seeding during the fall or early spring ensures that most of the seed germinates before dangerous summer temperatures.

4 SEED APPLICATION

4.1 Seed handling

Like with nursery seedlings, proper seed handling is necessary to avoid seed quality losses. Handling requirements depend on whether seed has been stratified or not. Once ordered and lifted from long-term storage, unstratified seed for fall seeding must be kept in cool and dry conditions until sown. In the field, seeds can be kept in coolers placed in the shade during operations (Figure 11 and Figure 12).

Figure 11. Seed handling at the site.

Figure 12. Seeds shipped in chilled insulated foam containers.

Stratified seed requires more careful handling once received. Seed stratification increases moisture content and kickstarts respiration and other physiological processes (Kolotelo et al. 2001). Once a seed is stratified, it is fragile and using up its carbohydrate reserves, so care must be taken to sow it as soon as possible. After ordering stratified seeds and prior to seeding, they should be kept in a well-aerated open container in a fridge under stratification conditions (2-5 °C) to prevent molding, premature germination and loss of viability (Kolotelo et al. 2001). In the field this can also be achieved with insulated containers and cold packs. Stratified seed should not be exposed to freezing temperatures, as the seed contents run the risk of crystallizing due to the higher moisture content (Kolotelo et al. 2001). During operations, avoid leaving seeds in the seed hopper overnight, to avoid losses to freezing temperatures, pre-germination or molding.

If stratified seed has too much excess moisture, it may cause jams within the seed delivery system. This can be solved by air drying the seed with minimal or no heat. Drying the seed down to approximately 20% moisture content, will also be necessary if delays occur preventing stratified seeds to be sown within 2-3 weeks, or if the seed starts to mold or germinate prior to seeding (Kolotelo et al. 2001). Seeds remaining after operations should be returned to the long-term seed storage facility as soon as possible.

4.2 Precision seeding systems

The Bracke S35.a seeder is a pneumatic linear seeder that delivers individual seeds from a hopper via a rotating seedwheel (Figure 13). Seed rate is set on a seeds per metre basis, and is based on the amount of seed divots in a seedwheel and its rotating speed. The size of the divots is matched to the seed size (Figure 14). The seeder connects to the prime mover's drivetrain and autoregulates the seedwheel speed accordingly to maintain a constant seed rate independent of machine speed (although it may also be used in tracked machines by overriding the autoregulation function and setting a constant seedwheel speed according to the average machine travel speed.) Other features include an optical metering sensor that counts the seed output and alerts the operator of any disruptions, and an onboard display that shows real time seed output and allows the operator to change seed rate settings easily (Figure 15).

The second seeder used in our trials was designed and manufactured in Alberta by Swedcan West Inc (Figure 16). The prototype observed in the trials is similar in concept to the Bracke S35.a: individual seeds pass from the seed chamber through an exchangeable rotating brass wheel that controls the seed rate. Unlike the Bracke seeder, the Swedcan's seeding rate does not automatically adjust to the prime mover speed; instead, the seed rate must be set in advance and then manually adjusted to one of three settings (low, medium, and high) depending on prime mover travel speed, to achieve a constant target seed rate.

Both the Bracke and the Swedcan seeders can be mounted on skidders and crawler tractors fitted with disc trenchers for row scarification.

Figure 13. Bracke s35.a seed metering system

Figure 14. Bracke S35.a seedwheel.

Figure 15. Bracke s35.a onboard display

Figure 16. Filling the hopper on a SwedCan seeder.

Other precision seeding systems for ground-based seeding have been used in the past elsewhere in Canada, primarily the Sigma TTS seeder and the Canadian-made Bartt Mark IV, and are described in detail in Reynolds 1997.

4.3 Site preparation

Fresh site preparation is required when direct seeding, as the surface area contact between seeds and soil is greater with freshly disturbed soil, protecting seeds from drying out and providing moisture through capillary movement of water. This is not a problem in ground-based mechanized direct seeding, as seeding is done simultaneously with site preparation.

The site preparation objective for direct seeding is fresh mineral soil exposure, and the end result should resemble scarification more than disc trenching. This is particularly the case in dry pine sites with a thin LFH, the typical candidate site for direct seeding, where raised microsites or deep scarification may be detrimental to the site. To achieve minimal scarification, the pressure on the discs should be minimal, and the disc angle should be widened to achieve flatter rows. Worn-down or short teeth on the discs also help achieve minimal scarification. The t26a disc trencher is more versatile in this respect than the more common TTS disc trencher, and can achieve less aggressive, shallower rows without the added width (Figure 17). On more difficult sites, sites with high slash loading or with thick LFH layers, a front V-blade or a more aggressive disc angle might be needed to expose mineral soil. Operators must keep the seedbed objective in mind and monitor the resulting site preparation as the disc settings will vary site with LFH depths, soil depths and slash loads (Figure 18).

Figure 17. Disc scarification with Bracke t26a trenchers, resulting in narrower strips.

Figure 18. Disc scarification with TTS trenchers.

4.4 Timing of operations

One of the advantages of direct seeding compared to tree planting is flexibility in timing of operations and the possibility to seed during the fall. Direct seeding should be timed so that germination and early growth coincides with the increased soil moisture during spring (May–June) so that seedlings are well-established before the hot and dry months of summer. This can be achieved by seeding unstratified seed in the fall or using stratified seed in the spring.

In the 2013-2017 direct seeding trials there is not enough data on the effects of spring vs fall seeding in establishment rates, due to the greater influence of weather factors (Appendix 1). Although spring seeding (May–June) with stratified seed minimizes the time that the seed is exposed to predation and fungus and losses to heat (Winsa & Sahlén, 2001; Birkedal, 2006), lodgepole pine has been proven to overwinter under snow well for germination the following year (Bergsten & Sahlén, 2008), as has been observed in B.C. trials. In fact, in nature, lodgepole pine seedfall in B.C. occurs over a 5 week period in September-October, when the cones mature (Armit, 1966). Research in northern Finland has also found that lodgepole pine fall seeding results have similar establishment to spring seeding if done in the late fall (October and later) (Hyppönen & Hallikainen, 2011). Seeding in the summer (July-August), however, with either stratified or unstratified seed, can result in increased seed and germinant losses to heat, drought or predation.

Seeding in spring with stratified seed can be operationally challenging, however. Stratification requires seed to be sowed within two to three weeks to maintain seed viability (Kolotelo et al., 2001), which can complicate logistics if unforeseen operational delays occur. Problems can arise with mold or pre-germination if seed is not handled well, or if it's too moist it may cause jams in the seed delivery mechanism of the seeder. See Seed Handling section for more details.

4.5 Cost

The relatively low cost of direct seeding compared to planting is the primary reason for choosing to direct seed. In B.C., the seed is procured by the licensee at the costs outlined by the B.C. Tree Seed Centre. Under the current fee schedule, the cost of using B-class lodgepole pine seed (with a seed weight of 337 seeds/g and at a seed rate of 11 100 seeds/ha) is $49/ha[3] (Tree Seed Centre, 2011). Treatment productivity is not significantly affected by the addition of direct seeding and remains the same as for site preparation operations (skidder and crawler tractor trenching productivity ranges from 0.8-1.0 ha/scheduled machine hour (SMH) and 0.6-0.8 ha/SMH respectively). For a detailed cost comparison of direct seeding and planting, see the sample scenario in the comparison and planning tool in Appendix 3. This comparison tool is available to FPInnovations' members upon request.

5 MONITORING

Regeneration surveys on direct seeded sites should be performed 3 to 5 years after seeding, ideally. During the first two years, germinants are very small and may not be easily observed, and thus survey results may not properly reflect stocking (Figure 19). Most of the germination will have expressed itself by the third year, and if regeneration delay timeline is short or there is reason to believe treatment may not have been successful, a survey can be done after the third year. However, changes in stocking will still be highly dynamic due to early mortality, delayed germination and natural ingress for up to 5 years.

[3] Seed cost can vary with collection area and cone collection methods

Figure 19. Two one year old lodgepole pine germinants.

6 MANAGEMENT IMPLICATIONS

6.1 Total reforestation costs

The need for juvenile spacing, or pre-commercial thinning, has not been an issue in any study site (Appendix 1). No trial sites are expected to require spacing, even those seeded at rates of upwards of 20,000 seeds/ha. Spacing of lodgepole pine is commonly considered in British Columbia when densities approach 25,000 countable conifers per hectare, whereas the highest stocking in the study sites was 6,000 stems/ha after three years.

Planting or fill-planting will be necessary if direct seeding fails to achieve the stocking objectives for the site. Out of the 23 study sites assessed in our trials, 14 failed to achieve the minimum stocking, mostly in the southern interior due to frequent summer droughts experienced in the region in 2015 and 2017 (Appendix 1). While there is a higher risk of having to fill-plant when relying on direct seeding, total reforestation costs may still be lower by direct seeding first and then fill-planting than by tree planting from the outset. Forest managers need to understand at which level of non-satisfactorily restocked area direct seeding + fill planting becomes uneconomical. A sample calculation is given in Figure 20, where the break-even point is found at 50% non-satisfactorily restocked area. The planning tool outlined in Appendix 2 can help forest managers explore the total cost of a plantation up to free-growing status under different scenarios.

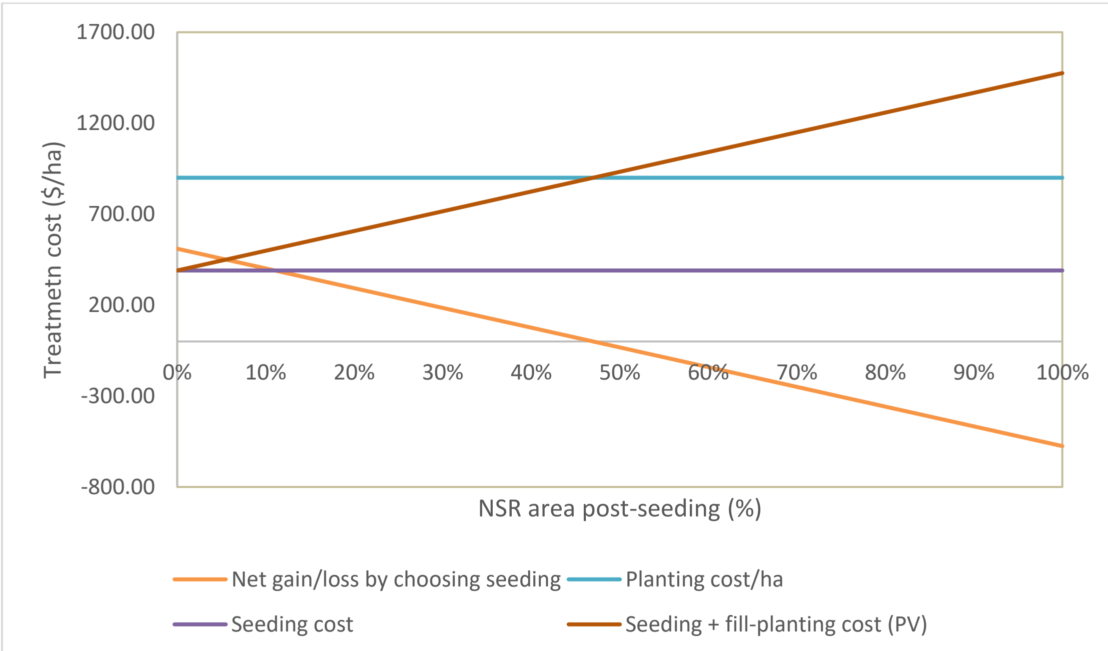


Figure 20. Example of a break-even calculation when comparing direct seeding and fill-planting vs. planting.

6.2 Impact on green-up and rate of cut

The use of direct seeding instead of tree planting of nursery stock could have an effect on green-up timelines and timber supply due to the longer establishment period and through the use of stand seed vs improved orchard seed. Under current conditions, the limited supply and high cost of improved orchard seed precludes it from being used in direct seeding. More research is recommended on the impact of the longer establishment timelines on rate of cut before large-scale implementation of direct seeding.

7 CONCLUSION

Ground-based mechanized direct seeding of lodgepole pine has shown promise in recent trials in B.C. This guide is based on observations from 2013-2017 direct seeding trials in British Columbia and explores ways to minimize this risk and implement direct seeding on the ground. A companion planning and cost comparison tool is available to members that helps explore the cost of direct seeding treatments in different scenarios. This guide and the planning tool are meant to be a starting point to help forest managers develop direct seeding prescriptions where needed. Local knowledge will have to be developed to further dial in the region-specific requirements for successful use of direct seeding.

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9 APPENDIX

9.1 Appendix 1. 2013-2017 Direct seeding trials in B.C.

The current reforestation challenges posed by salvage logging following large-scale disturbances in western Canada, such as wildfire and mountain pine beetle (MPB), warrant the need for cost-effective reforestation strategies. This is particularly the case in areas previously managed for natural regeneration but where the seed source might no longer be viable. Direct seeding is enjoying renewed interest in western Canada as a way to address these reforestation issues. While direct seeding has been explored in British Columbia in the past with mixed results, recent innovations in mechanical seed application technology and better understanding of the factors that influence germination and establishment have made it a potential reforestation alternative.

Since 2011, FPInnovations has established a series of field trials using different tree species, seeders, and site preparation treatments on a range of Biogeoclimatic Ecosystem Classification (BEC) subzones, with the objective of identifying which factors affect the success of germination and establishment of seed from mechanical direct seeding. This report presents early establishment results from 23 direct seeding trial sites across B.C., established from 2013 to 2017 in partnership with West Fraser, Tolko, Canfor, Conifex, Weyerhaeuser, BC Timber Sales, Doug Brophy Contracting, and Interior Silvi-Services. The objective was to determine the factors affecting reforestation through direct seeding in B.C. This report describes these operations as well as stocking results for the first 2-3 years.

9.1.1 Site and treatment description

Trial sites were identified in the Cariboo-Chilcotin (Table 2) central B.C. (Table 3) and the southern interior[4] (Table 4).

Table 2. Overview of Cariboo-Chilcotin direct seeding trial sites

Study block	100K Road	Aneko	Moffat Lake
Location	Williams Lake	Williams Lake	Williams Lake
BEC subzone and site series	SBPSmk-01	MSxv-01	SBPSmk-01,06,07
Species	Pli (100%)	Pli (100%)	Pli (80%) Sx (20%)
Seed rate (seeds/ha)	11 100	7 400	7 400
Stratification (Y/N)	N	N	N
Date seeded	September 2013	August 2014	October 2014

[4] The approach of the Kelowna and Salmon Arm trials was different than the previous trials. FPInnovations assessed the southern interior sites after operations, with a focus on early establishment dynamics after direct seeding. As such, machine and specific site preparation configurations are unknown. On these sites, every germinant in a plot was marked and the plots were visited yearly to determine early mortality and survival rate.

Seeder	Bracke S35.a	Bracke S35.a	Swedcan (prototype)
Prime mover and site preparation equipment	John Deere 748E skidder with T26a trenchers and a front V-blade	John Deere 748E skidder with T26a trenchers and a front V-blade	TD20G Dresser crawler tractor with TTS trenchers and a front V-blade
Site preparation	Disc scarification	Disc scarification	Disc trenching

100K Road: well-drained mesic site in the SBPSmk (Sub-boreal pine and spruce moist and cool) subzone with slopes ranging from 5% to 20% and with a mix of exposed southern and northern aspects (Figure 21). The northern aspects had moderate mountain alder cover. Germination plots were placed in both aspects to identify their effect on germination and growth. The Bracke T26a disc trencher's negative pressure feature was used to lightly scarify the soil to expose enough mineral soil for the seeds, while keeping soil disturbance to a minimum (Figure 22).

Figure 21. 100K Road study site

Figure 22. Bracke S35.a seeder mounted on a skidder with T26a two-row disc trencher.

Aneko: MPB salvage block within the MSxv (Montane Spruce very dry very cold) subzone in a zonal site (Figure 23). Slopes were variable with an average of 15% and with short steep slopes of 35%–40%. Small areas of dry rocky ground with no LFH cover were scattered throughout. The collaborator's establishment target for this site was 3 500 stems/ha. Site preparation was the same as in 100K Road.

Figure 23. Aneko study site

Moffat Lake: A wet site within the SBPSmk (moist and cool) subzone. The block had a flat topography with gentle slopes ranging from 0% to 15% and an average of 5%. Major limiting factors to conifer regeneration in the trial area included winter damage and frost during the growing season, and high slash loads (Figure 24). A prototype of the Swedcan seeder was tested for the first time in this trial (Figure 25). Trenches were prescribed to be more aggressive than those in the 100K Road and Aneko trials after preliminary results from first-year germination measurements at 100K Road suggested that germination depended heavily on mineral soil exposure, and that light scarification could potentially fail to expose enough mineral soil in slash-heavy sites.

Figure 24. TD20G Dresser crawler tractor fitted with TTS trenchers and a V-blade attachment navigating high slash loads.

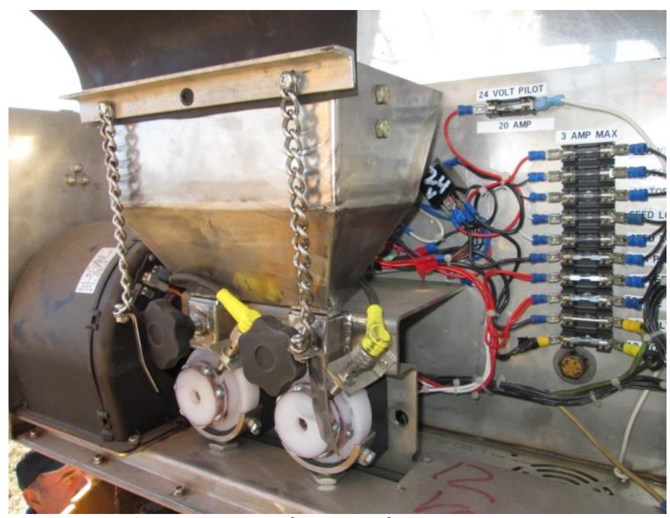

Figure 25. Swedcan seeder prototype.

Table 3. Overview of northern B.C. direct seeding trial sites

Study block	Barlow	Teardrop	Moose Lake	Witter	Trout	Shuschona Creek
Location	Vanderhoof	Fort St. James	Tumbler Ridge	Mackenzie	Fraser Lake	Fort St. James
BEC subzone and site series	SBSmc2-01	SBSmk1-06	ESSFmv2-04 and BWBSwk1-01	SBSmk1-03	SBSmc2-01	SBPSmk1 – 03, 01
Species	Pli (100%)	Pli (100%)	Sx (100%)	Pli (90%) Sx (10%)	Pli (100%)	Pli (75%) Sx (25%)
Seed rate (seeds/ha)	18 500	37 000	11 100, 18 500, and 29 600	11 100	7 400 and 11 100	11 100
Seed rate (seeds/m)	5	10	3, 5, and 8	3	2 and 3	3
Stratification (Y/N)	Y	N	N	N	N	N
Seed germination capacity (%)	97	97	78	Pli: 96 Sx: 82	95	Pli: 94 Sx: 94
Date seeded	June 2014	October 2014	August 2015	September 2015	October 2015	September 2017
Seeder	Bracke S35.a	Bracke S35.a	Bracke S35.a	Bracke S35.a	Bracke S35.a	Bracke S35.a
Equipment	John Deere 748G-III skidder with TTS trenchers and a V-blade attachment	John Deere 748G-III skidder with TTS trenchers and a V-blade attachment	John Deere 748G-III skidder with TTS trenchers and a V-blade attachment	John Deere 748G-III skidder with TTS trenchers and a V-blade attachment	CAT D6H XL dozer with TTS disc trenchers and a V-blade attachment	John Deere 748G-III skidder and CAT D7R XR crawler tractor with TTS trenchers and a V-blade attachment
Site preparation	Disc scarification	Disc scarification	Disc scarification	Disc scarification	Disc scarification	Disc scarification (non-rotating discs)

Barlow: A zonal site within the SBSmc2 (Babine moist cold subzone) (Figure 26). It featured gentle slopes, small areas of wet ground and silty clay soils. The high seed rates used were expected to offset rust mortality, as the licensee managed for high establishment rates of up to 10 000 stems/ha at free to grow. It was seeded in the spring with stratified seed.

Teardrop: Located in a poor-mesic site in the SBSmk1 (Mossvale moist mool) subzone (Figure 27). The block had gentle slopes with silty loam soils and patches of wet ground and sandy soils. While it was on the same operation as Barlow, the decision was made to seed in the fall after a droughty summer in the area.

Moose Lake: Two experimental units were identified within the block according to BEC classification. Each unit had three treatment units of approximately 1 ha, each seeded with a different seed rate. Both units were seeded with interior spruce. Because of the lower expected establishment rate for spruce, they were seeded at high seed rates (Greene & Johnson, 1998).

> BWBSwk1-01: Low-lying area within the block, with gentle slopes (5%–20%) and small non-productive wet areas present but excluded from the trial treatment units. Soils were poor, mesic to subhygric silty clay loams (Figure 28).
>
> ESSFmv2-01: unit with slopes of 10%–25% and fine silty clay soils, mesic to subhygric moisture regime and medium to rich nutrient regime, with deeper soils than the BWBS unit. Brush coverage was moderate to high at the time of seeding, with highly competitive oak fern, cow parsnip, fireweed, and white rhododendron vegetation complexes (Figure 29)

Figure 26. Barlow study site.

Figure 27. Teardrop study site.


Figure 28. Moose Lake (BWBS) study site **Figure 29. Moose Lake (ESSF) study site.**

Witter: Located in the SBSmk1-03 (Mossvale moist cool subzone), in a poor to very poor, subxeric site (Figure 30). The low slash levels, lack of vegetation competition, and the evenly flat ground make this block ideal for direct seeding. Regeneration prescriptions in the area tended to be scarification and natural regeneration, but as the seed quality has decreased with age since the mountain pine beetle attack, natural regeneration has become less reliable. Stands in the area are susceptible to western gall rust and direct seeding is expected to help meet the cooperator's seedling establishment objective of 5 000 stems/ha to offset any rust mortality.

Trout: The block is a zonal site within the SBSmc2 (Babine moist cold) subzone with gently rolling terrain (Figure 31). High slash loads found throughout. Half the treatment area with coarser soil was sown at a seed rate of 2 seeds/m and the other half with finer soil was seeded at 3 seeds/m, or approximately 7 400 and 11 100 seeds/ha, respectively. A portion of the block was not seeded and was planted in the spring of 2016.


Figure 30. Witter study site. **Figure 31. Trout study site.**

Shuschona Creek: Unit was divided into four treatment units to capture direct seeding establishment sites with different soil moisture regimes and trafficability in the SBPSmk1 (Figure 32). The study area comprised a subhygric-mesic site, a submesic-mesic site, a xeric site with sandy soils, and in mesic sites with difficult trafficability due to high slash load. Sites had gentle slopes and soils were silty loams throughout except for the sandy loam soils in the xeric unit. The collaborator was looking for minimal soil disturbance so the discs were set at non-rotating and widest angle to achieve a totally flat scarification, the least aggressive scarification in these trials. The high-slash site was done with rotating discs and a sharper angle on the discs in order to get the desired mineral soil exposure.


Figure 32. Shuschona creek study site.

Table 4. Overview of southern interior B.C. direct seeding trial sites

Study block	White-foot Main	Buck Lake	Beautiful Main	Salmon River	Glimpse Lake	Allenby		China Creek
						Row scarification	Stumping	Road rehabilita-tion
Location	Kelowna	Kelowna	Salmon Arm	Salmon Arm	Salmon Arm	Princeton	Princeton	Princeton
BEC subzone and site series	ESSFdc1-01	MSdm1-01	IDFdk2-01	MSdm2-01	MSdm2-01	IDFxh1-06	IDFxh1-06	MSdm2-2 and MSdm2-5
Species	Sx (100%)	Pli (80%) Lw (20%)	Fdi (100%)	Pli (70%) Sx (30%)	Pli (70%) Sx (30%)	Fdi (100%)	Fdi (100%)	Pli (100%)
Seed rate (seeds/ha)	12 000	8 000	8 000	8 000 and 9 000	8 000	4,200	4,400	27,000
Stratification (Y/N)	N	N	Y	N	Y	N	N	N
Seed germination capacity (%)	90	93/76	87	91/76	--	98	98	95
Date seeded	July 2015	July 2015	June 2015	May 2015	May 2015	June 2017	June 2017	June 2017
Seeder	Swedcan	Swedcan	Swedcan	Swedcan	Swedcan	SwedCan on CAT D7R XL crawler tractor with front rake and TTS trenchers	Custom seeder on Kobelco Excavator with bucket and thumb	Custom seeder on Kobelco Excavator with bucket and thumb
Site preparation	Disc scarification	Disc scarification	Disc scarification	Disc scarification	Disc scarification	Disc scarification	Stumping and scalping	Temporary road rehabilitation

<u>Whitefoot Main</u>: Located in the lower elevations of ESSFdc1 (Engelmann spruce – subalpine fir Okanagan dry cold subzone), in a zonal site series (Figure 33). The topography was characterized by benches and rocky slope breaks, with slopes ranging from 5% to 60% and an average of 30%. Soils were moderately deep and consist of sandy loam. The previous stand consisted of lodgepole pine, with interior spruce, subalpine fir, and western larch components.

Buck Lake: Located in a zonal site series in the MSdm1 (Okanagan dry mild) subzone near Kelowna (Figure 34). It had gentle rolling slopes of 5% to 30% with westerly aspects. Soils were sandy loams throughout. The previous stand consisted of lodgepole pine and western larch, with Douglas-fir and subalpine fir components. The block had an unevenly distributed overstorey layer of mature western larch and Douglas-fir leave-trees at an approximate density of 5 stems/ha.

Figure 33. Whitefoot Main study site.

Figure 34. Buck Lake study site.

Beautiful Main: Mesic to subhygric site within the IDFdk2 (Interior Douglas-fir Thomson dry cool) subzone, located near Salmon Arm (Figure 35). Slopes ranged from 0% to 30% with north-westerly aspects. The previous stand consisted of mostly Douglas-fir with a lodgepole pine component. The block had moderate vegetation competition from forbs and grasses shortly after seeding.

Salmon River: Located in the mid-lower elevations of the MSdm2 (South Thomson dry mild) subzone, in a zonal site (Figure 36). Slopes ranged up to 35% with north-westerly aspects. The previous stand consisted of an lodgepole pine–interior spruce mix, with minor subalpine fir and Douglas-fir components.

Figure 35. Beautiful Main study site

Figure 36. Salmon River study site.

Glimpse Lake: Like the Salmon River block, this block was located in a zonal site series of the MSdm2 subzone. It was relatively flat, with an average slope of 13%. Soils were fine and shallow, ranging from sandy loams to fine sandy loams. There is evidence of high cattle use throughout the block. It was seeded with stratified lodgepole pine seed to serve as a comparison to the Salmon River block, an ecologically similar site seeded with unstratified seed.

Allenby: The Allenby trial took place in two ecologically similar sites close to each other, in the IDFxh1 (Okanagan very dry hot) subzone (Figure 38). Because of root rot occurrence, one site was stumped and seeded with a custom pneumatic seeder mounted on an excavator (Figure 41). Where stump density was not sufficient, the operator created scalps to achieve 1200 site prepared spots per hectare, on which seed shots (averaging 4 seeds/shot) were placed. The second site was scarified and seeded with a disc trencher. Both were seeded with Douglas-fir.

Figure 37. Glimpse Lake study site.

Figure 38. Allenby study site.

China Creek: The trial in China Creek also divided in two nearby sites with different moisture regimes: a warm and dry southwest exposure (Figure 39) and a nearby site with a north east exposure and increased soil moisture (Figure 40). An excavator and a custom pneumatic seeder (Figure 41) were used to deliver seed as the excavator rehabilitated temporary block roads (Figure 42). Lodgepole pine seed was used at a rate of 27,000 seeds/ha (or 660 seeds/m of road).

Figure 39. China Creek (subxeric) study site.

Figure 40. China Creek (subhygric) study site.

Figure 41. Custom pneumatic seeder on excavator arm.

Figure 42. Temporary road rehabilitation and seeding.

9.1.2 Methods

A total of ten pre-treatment transects and ten post-treatment plots were established systematically over a study area, with the exception of some southern interior trials. These transects were 20 m in length and measured pre-existing terrain characteristics including slash loading, soil depth, rock content, stump density and size. The post-treatment plots (measured after site preparation), were 20 × 5 m (100 m^2) and ran longitudinal to the trench, with the starting point located in the centre of the disc-trencher pass. Trench dimensions (width, depth), trench density, site preparation quality, and trench seedbed quality were measured in every plot.

Germination assessments were done after the second growing season except where otherwise noted. Germination plots in row scarified sites were 20 × 5 m (100 m^2) and ran longitudinal to the trencher pass and measured the number of seeded and natural regeneration, as well as species, height, position along the trench, and growing substrate. A second 3.99 m radius (50 m^2) circular plot was established at the 10 m mark of each rectangular plot to measure well-spaced stocking. On some southern interior sites (all except Allenby and China Creek), germination assessments were done as in the rest of the trials, with the addition that plots were 10 × 5 m (50 m^2) and were measured yearly. Each individual seedling was marked with a pin flag and their survival followed in subsequent years for a more detailed look at early dynamics of direct seeding. Stocking results are reported for all trials, as well as factors that affected germination and establishment.

9.1.3 Results and discussion

9.1.3.1 Pre- and post-treatment site conditions

Table 5. Pre-treatment site conditions

Unit	Slash loading (m^3/ha)	Slash heights (cm)	Rough-ness class	Soil texture	LFH layer depth (cm)	Soil depth to rock (cm)	Rockiness (%)	Stump density (no./ha)
100K	284 (± 68)	18	1	---	6.4	16	85	1230
Aneko	110 (± 43)	12	1	---	2.9	17	100	660
Moffat Lk	300 (± 62)	27	1	---	8.4	27	62	910
Barlow	227 (±43)	20	1	Silty Clay	6.4	19.3	69	---
Teardrop	209 (±83)	20	1	Silty Loam, Sand	5.4	19	48	---
Witter	46 (±61)	4	1	Sandy, Loam, Loamy Sand	3.3	13	43	1033
Moose Lk (ESSF)	289 (±252)	21	1	Silty Clay	8.5	18	80	467
Moose Lk (BWBS)	223 (±244)	12	1	Silty Clay Loam	6.3	19.8	80	1667
Trout	170 (±146)	5	1	Silty Clay - Loamy sand	3.2	22.1	80	1333
Suschona Ck (subhygric)	136 (±30)	12	1	Silty Loam	3.8	--	--	867
Suschona Ck (submesic)	179 (±33)	14	1	Silty Loam	6.3	--	--	1733
Suschona ck (xeric)	146 (±--)	10	1	Sandy Loam	0	--	--	1200
Suschona Ck (high slash mesic)	236 (±--)	20	1	Silty Loam	8	--	--	3500

Table 6. Post-treatment site conditions

Unit	Trench width (cm)	Trench depth (cm)	Distance between trenches (m)	Distance between passes (m)	Treatment density (rows/ha)	Suitable seedbed (% of trench area)
100K	28	8	1.8	5.4	37	72
Aneko	38	7	1.8	5.7	35	88
Moffat Lake	61	19	2.2	5.9	34	67
Barlow	63	---	2.1	6.2	32	---
Teardrop	64	---	2.0	5.2	38	---
Witter	49	16	2.2	5.8	35	98
Moose Lake (ESSF)	54	13	2.2	5.7	35	68
Moose Lake (BWBS)	56	15	2.2	5.2	38	78
Trout	---	---	2.0	5.6	36	92
Shuschona Ck (subhygric)	84	8	2.1	5.3	38	83
Shuschona Ck (submesic)	84	6	2.1	4.9	41	76
Shuschona Ck (subxeric)	86	9	2.1	5.0	40	90
Shuschona Ck (mesic high slash)	66	10	2.1	5.8	35	60
Whitefoot	38	16	2.2	5.4	37	71
Buck Lake	33	13	2.1	5.5	36	64
Glimpse Lake	30	11	2.1	5.3	38	59
Salmon River	47	10	2.1	5.6	36	65
Beautiful Main	55	18	2.2	4.7	42	68

Missing values not assessed

Table 7. Site preparation and seedbed quality

Site preparation and seedbed condition	100K	Ane-ko	Moff at Lk	Wit-ter	Moos e Lk (ESSF)	Moose Lk (BWBS)	Trout	Shush-chona (sub-hygric)	Shush-chona (subme-sic)	Shush-chona (subxe ric)	Shushch ona (high slash)
Successful site preparation (%)	72	88	80	98	86	93	98	98	84	96	83
Suitable seedbed (%)	72	88	67	98	68	78	92	83	76	90	60
Mixed mineral/humus	14	9	4	5	37	41	16	0	0	0	13
Humus	0	0	1	0	6	1	0	0	0	0	
Mineral soil	58	79	62	93	25	36	76	83	76	90	47
Unsuitable seedbed (%)	0	0	13	0	18	15	6	15	8	6	23
Disturbed loose organic	0	0	6	0	2	8	0	15	8	6	23
Exposed rock	0	0	3	0	1	3	0	0	0	0	0
Berm fallback/covered trench	0	0	0	0	7	4	0	0	0	0	0
Exposed root	0	0	0	0	8	0	6	0	0	0	0
Standing water	0	0	4	0	0	0	0	0	0	0	0
Unsuccessful site preparation (%)	28	12	20	2	14	7	2	2	16	4	17
Suitable seedbed (%)	0	1	0	0	0	0	0	0	0	0	0
Soil pre-disturbed	0	1	0	0	0	0	0	0	0	0	0
Unsuitable seedbed (%)	28	11	20	2	0	7	0	2	16	4	17
Undisturbed litter	8	3	2	0	0	0	1	0	0	0	0
Undisturbed due to vegetation	2	0	0	2	1	0	0	0	0	0	0
Undisturbed due to slash	6	4	12	0	6	2	0	1	10	1	8
Undisturbed due to stump	5	3	6	0	7	5	0	1	5	3	9
Undisturbed due to boulder	1	1	0	0	0	0	1	0	1	0	0
Other	6	0	0	0	0	0	0	0	0	0	0

9.1.3.2 Stocking

First-year germination results were measured at 100K Road and are shown in Table 8. Third-year (at 100K Road) and second-year (at Aneko and Moffat Lake) stocking results are shown in Table 9. Results show 18% establishment at 100K Road after the first growing season. Germination continued to improve such that by the third year, the block could be considered satisfactorily restocked, with 48% establishment from seed and an average seeded height of 7.9 cm (Figure 43). Stocking density and average height in the northern and southern aspects of the block were compared, and while both metrics were slightly higher in the shaded north-facing section, no significant difference was found at this time (α=0.05).

Table 8. First year establishment at 100K Road

	Stocking density (stems/ha)	Average height (cm)
Naturals	900 (±346)	5.1
Seeded germinants	1 780 (±397)	2.8
Total	2 680 (±591)	3.5

Figure 43. Three-year-old seedlings, 100K Road.

Figure 44. One-year-old seedling, Moffat Lake.

By comparison, establishment was null at Moffat Lake and poor at Aneko: second-year establishment from seed in these sites was slightly lower than first year establishment at 100K (17% at Aneko and 13% at Moffat Lake)(Table 9). While it is difficult to identify a main cause, a number of site moisture-related factors could have played a role in the low establishment: weather during the 2015 growing season was unseasonally dry and may have hindered germination during the critical first growing season (Appendix 1a). In addition, site moisture regimes in Aneko and Moffat Lake may represent the upper and lower site moisture limits of where direct seeding is a feasible treatment option. While an adequate moisture supply is necessary for germination, saturated conditions may deprive the seeds of the oxygen they need to germinate (Kolotelo et al., 2001). These limiting factors were exacerbated by the lower prescribed seed rate (7 400 seeds/ha).

Table 9. Establishment results from Cariboo-Chilcotin direct seeding trials after 2 and 3 growing seasons

	100K Road[a]	Aneko	Moffat Lake
Total stocking (stems/ha)	6280 (±750)	5720 (±4707)	2810 (±1765)
Total species composition	$Pli_{95}Sx_5$	Pli_{100}	$Pli_{95}Sx_5$
Seeded stocking (stems/ha)	4800 (±669)	1220 (±596)	930 (±663)
Seed establishment (%)	48	17	13
Seeded species composition	Pli_{100}	Pli_{100}	$Pli_{95}Sx_5$
Seeded germinant height (cm)	7.9	3.0	4.0
Well-spaced stocking (stems/ha)	1000 (±122)	1100 (±191)	720 (±166)
M-capped well-spaced stocking (stems/ha)[b]	980 (±102)	1020 (±115)	720 (±166)
Seeded well-spaced stocking (stems/ha)	720 (±157)	460 (±134)	480 (±125)

[a] Results after three growing seasons

[b] M value of 6 (based on target stocking of 1200 stems/ha)

Spruce establishment in both treatment units at Moose Lake was very poor, at less than 1% (Table 10). Germinants were found only in brush-free patches; however, both units within the block (particularly the rich ESSF unit) had developed high coverage of competitive vegetation complexes (reedgrass, fireweed, lady fern) that completely colonized and shaded the trenches preventing germination (Figure 8).

At Barlow, 82% of the assessed seeded germinants germinated during the second growing season after seeding. Such low first-year germination is likely due to a prolonged drought in the area during the summer of 2014 (Appendix 1a). These results suggest that stratified lodgepole pine seeds are capable of surviving on the ground and germinating at least one year after seeding, as with unstratified seed.[5] Seeded stocking and average height at Teardrop were similar to Barlow despite having had only one growing season at the time of measurement.[6]

[5] Germination of unstratified lodgepole pine has been observed up to 4 years after seeding in past trials.
[6] On a later regeneration survey in 2017, Teardrop was satisfactorily restocked with small not satisfactorily restocked pockets (NSR), but Barlow was found to be NSR and scheduled for planting.

Table 10. Establishment results from northern B.C. direct seeding trials after 1 and 2 growing seasons.

	Barlow	Tear-drop[a]	Moose Lake		Wit-ter	Trout		Shuschona Creek[a]			
			ESSF	BWBS		2 seeds/ha	3 seeds/ha	Sub-hygric	Sub-mesic	Xeric	Mesic high slash
Total stocking (stems/ha)	6630 (±2224)	5170 (±1631)	493 (±171)	747 (±228)	1470 (±393)	2860 (±1504)	1260 (±321)	1,927 (±191)	1,099 (±623)	348 (±314)	892 (±606)
Total species composition	$Pli_{95}Bl_5$	Pli_{90} Bl_5Sx_5	Pli_{60} Sx_{20} Bl_{20}	Pli_{85} Sx_{15}	Pli_{90} Sx_{10}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}
Seeded stocking (stems/ha)	3020 (±625)	2970 (±397)	33 (22)	93 (47)	989 (±187)	1680 (634)	880 (±297)	1,927 (±191)	1,099 (±623)	348 (±314)	892 (±606)
Seed establish-ment (%)	15	7	0.1-0.3	0.3-0.9	10	24	9	18	10	3	9
Seeded species composition	Pli_{100}	Pli_{100}	Sx_{100}	Sx_{100}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}	Pli_{100}
Seeded germinant height (cm)	2.7	2.7	3.4	4.0	5.4	6.5	4.5	1.5	1.4	1	1.5
Well-spaced stocking (stems/ha)	1260 (±548)	1080 (±464)	--	--	1044 (±127)	1160 (±249)	520 (±217)	--	--	--	--
M-capped well-spaced stocking (stems/ha)[b]	1140 (±256)	1040 (±337)	--	--	1022 (±108)	1080 (±171)	520 (±217)	--	--	--	--
Seeded well-spaced stocking (stems/ha)	940 (±348)	900 (±396)	--	--	622 (±108)	1040 (±249)	400 (±234)	--	--	--	--

[a] Results after one season

[b] M value of 6 (based on target stocking of 1200 stems/ha)

Figure 45. Competing vegetation at Moose Lake.

Establishment within a block tended to have a patchy distribution, and was tied to site variability in soil texture and moisture regime. In Teardrop, small pockets of pure sand and areas with standing water were not satisfactorily restocked. Similarly, in Trout, the treatment area with coarser soils (but not pure sand) had better establishment than the area with finer silty soils. In the Shuschona Creek trial, xeric areas with pure sand, and areas with poor site preparation quality due to high slash, were not sufficiently stocked, as opposed to the subhygric and submesic strata.

Teardrop, Witter, and parts of Trout and Shuschona Creek are on track to meet the minimum stocking standards at regeneration delay without any further treatment if germination continues into the third year and there is minimal mortality. Total stocking, however, will likely not reach the high densities required to offset rust mortality.

Establishment was low for all of the southern interior sites, with 6–10% lodgepole pine establishment rates (Table 11). Germinant survival was hindered by extremely dry growing seasons in 2015 and 2017 in the southern interior (Appendix 1a). Heavy grass ingress was also an issue in Salmon River, Glimpse Lake, and Beautiful Main. Unlike previous trials, actual seed rate was not verified on site and could have also been an issue.

Table 11. Second-year establishment results from southern interior direct seeding trials

	White-foot Main[a]	Buck Lake	Beauti-ful Main	Salmon River	Glimpse Lake	Allenby		China Creek	
						Row scarified	Stumping	Subxeric	Subhygric
Total stocking (stems/ha)	1100 (±984)	1317 (±531)	420 (±360)	2200 (1150)	1020 (±511)	1330 (±542)	1370 (±486)	0	120 (±136)
Total species composition	$Pli_{90}Bl_{10}$	Pli_{50} $Lw_{30}Fdi_{10}$ Sx_5 Bl_5	Fdi_{80} $Pli_{10}Sx_{10}$	Pli_{60} $Bl_{20}Sx_{15}$ Fdi_5	$Pli_{95}Sx_5$	$Fdi_{96}Py_4$	$Fdi_{90}Py_{10}$	--	Pli_{100}
Seeded stocking (stems/ha)	0	733 (281)	220 (±168)	460 (251)	600 (±409)	0	0	0	120 (±136)
Seed establishment (%)	0	10	3	6	7	0	0	0	0.4
Seeded species composition	--	Pli_{60} Lw_{40}	Fdi_{100}	Pli_{60} Sx_{40}	Pli_{100}	--	--	--	Pli_{100}
Seeded germinant height (cm)	--	6.5	2.4	3.4	4.8	--	--	--	10
Well-spaced stocking (stems/ha)	340 (±219)	467 (±204)	180 (±128)	650 (±208)	500 (±206)	970 (±521)	1170 (±361)	0	120 (±136)
M-capped well-spaced stocking (stems/ha)[b]	340 (±219)	267 (±92)	180 (±128)	650 (±208)	500 (±206)	570 (±534)	1070 (±254)	0	120 (±136)
Seeded well-spaced stocking (stems/ha)	0	283 (±121)	140 (±123)	180 (±86)	360 (±210)	0	0	0	120 (±136)

[a] Results after one growing season.

[b] M value of 6 (based on target stocking of 1200 stems/ha), except in Beautiful Main (M=5) and Buck Lake (M=2) which had lower stocking standards.

Of all southern interior sites, Buck Lake had the best first-year establishment, as it had the least grass competition from all lodgepole pine sites. During second-year (2017) measurements, however, nearly half of first-year germinants (350 stems/ha) were found dead due to soil moisture deficit, as well as 533 stems/ha of germinants that had germinated during the second growing season. The resulting second-year stocking from seed was 733 stems/ha. This means that while 20% of the sown seed germinated, only 10% was established after the second year due to the drought experienced in 2017.

The rest of the blocks had low establishment due to drought and competition for moisture from grasses. The Whitefoot and Beautiful Main blocks were included in the study due to their use of interior spruce and Douglas-fir seed. Whitefoot was free of brush competition and had favourable site conditions, yet no germination from seeded interior spruce was observed after the first growing season. It is unlikely that this is due to delayed germination of spruce, as no spruce germination was observed in Glimpse Lake either, even after the second growing season.

9.1.4 Summary

Fourteen direct-seeding trials were established from 2013 and 2015 across B.C. and subsequently measured for preliminary germinant establishment after two years. Average lodgepole pine establishment was 14% and ranged from 6% to 33%. Out of the 23 sites, only 5 were on track to meet stocking targets, while 4 more had borderline results. The results are poor in most blocks and but are expected to be dynamic until the fifth-year reassessment milestone. Growing season precipitation remains an uncontrollable and largely unpredictable determinant of germinant establishment, and was likely the primary cause of failure in poorly stocked blocks, along with vegetation competition and potential seed rate delivery issues in certain blocks. These preliminary results show however that direct seeding can be effectively used as a reforestation tool if certain conditions are met. Careful site, species, and seed rate selection can reduce the risk of seeding failure.

9.1.5 References

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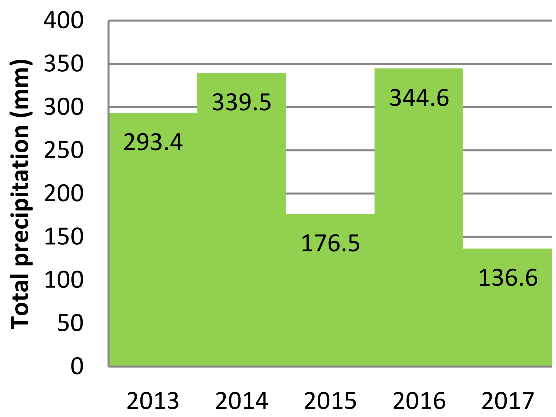
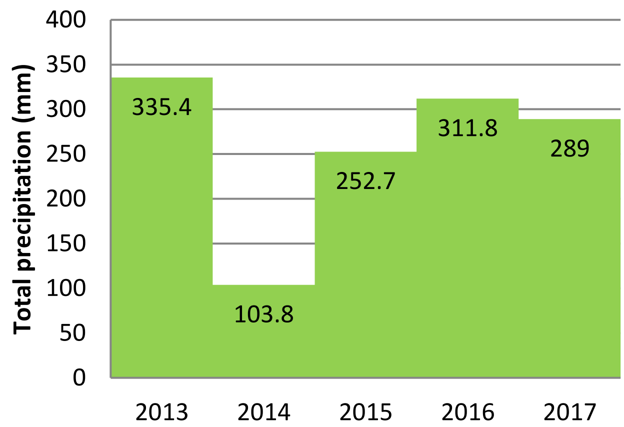
Kolotelo, D., Steenis, E. V., Peterson, M., Bennett, R., Trotter, D., & Dennis, J. (2001). *Seed handling guidebook*. Victoria, B.C.: British Columbia Ministry of Forests.

9.1.6 Appendix 1a. Total growing season precipitation

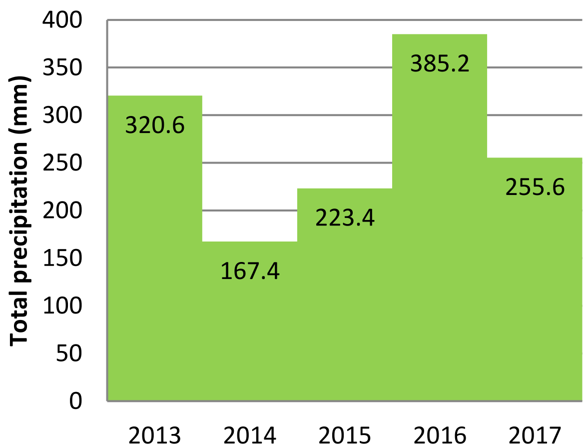
Williams Lake



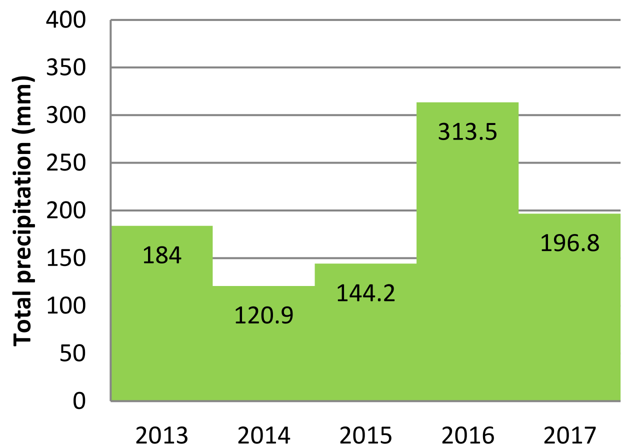
Mackenzie



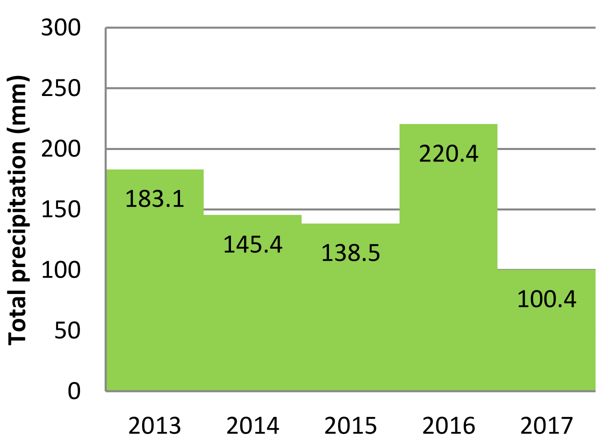
Vanderhoof



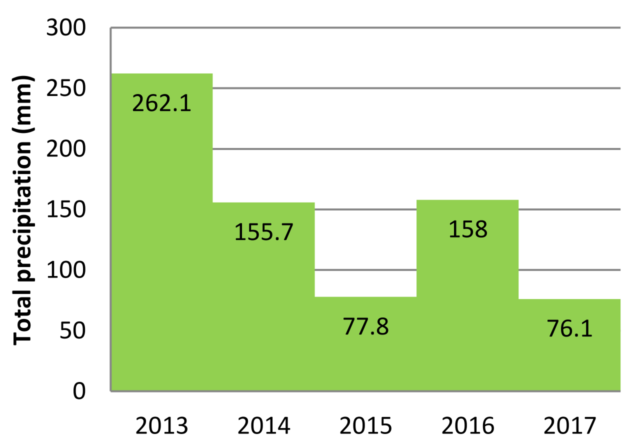
Fort St. James



Merritt



Kelowna



Data Source: Environment and Climate Change Canada.

9.2 Appendix 2. Biogeoclimatic zone constraining factors and mitigating action codes

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Vegetation		Temperature regime		Precipitation		Operability	
tor	Mitigating Action	Factor	Mitigating Action	Factor	Mitigating Action	Factor	Mitigating Action
V - Vegetation type	P - Site preparation	C - Cold (temperature prohibitive to germination/ early growth)	P - Site preparation	D - Dry (growing season moisture deficit typical)	P - Site preparation	S - Snow (depth or duration)	T - Time seeding during fall/winter to take advantage of drier soil conditions
V1 Woody shrubs	P1 Raised microsites: disturb vegetation, expose mineral soil and/or provide height advantage	C1 Short growing season	P1 Raised microsites: increase soil temperature and number of GDD	W - Wet (potential soil saturation)	P1 Raised microsites: decrease soil saturation	N - Sensitive soils (high organic content, susceptible texture and/or prone to saturation)	
V2 Herbaceous layer		C2 Growing season frosts	P2 Scalps/flat microsites: expose mineral soil to reduce diurnal temperature extremes		P3 Depressed microsites: seed into moisture receiving spots		
V3 Grass layer	P2 Scalps/flat microsites: remove vegetation and expose mineral soil	H - Heat (temperatures lethal to germination/ early growth)	T - Time seeding during fall/winter for earlier germination in spring		T - Time seeding during fall/winter to take advantage of moisture/ earlier germination		

9.3 Appendix 3. Direct seeding planning tool[7]

Inputs					
Seeding			**Planting**		
Name of Input	Input	Units	Name of Input	Input	Units
Seedlot specifications					
Germination capacity (viability)	93.00%	%			
Seeds per gram	337	seeds/g			
Seed cost	$1,482.00	$/kg			
Silviculture Conditions					
Expected establishment rate (seeding)	30.00%	%	Survival Rate (planting)	90.00%	%
Target stocking from seed	4800	stems/ha			
Expected natural ingress	800	stems/ha			
Initial Stand Establishment Cost					
Mechanical site prep machine cost	$300.00	$/ha	Mechanical site prep machine cost	300	$/ha
Seeder cost	$25.00	$/ha	Planting cost (labour)	$0.20	$/seedling
Width of rows (centre to centre)	5.4	metres	Seedling cost	$0.30	$/seedling
			Planting density	1200	stems/ha
Future Costs					
Juvenile spacing rate	$750.00	$/ha	Juvenile spacing rate	$750.00	$/ha
Years after initial seeding (spacing)	16	years	Years after initial planting (spacing)	16	years
% of area to be juvenile spaced	0.00%	%	% of area to be juvenile spaced	0.00%	%
Fill planting rate	$1.10	$/seedling	Fill planting rate	$1.10	$/seedling
Years after initial seeding (until fill plant)	3	years	Years after initial planting (until fill plant	3	years
% area to fill plant	0.00%	%	% area to fill plant	0.00%	%
Outputs					
Seeding			**Planting**		
Name of Output	Output	Units	Name of Output	Output	Units
Seed rate					
Target SPH from seed	4000	stems/ha			
Adjusted Survival Rate	27.9%	%			
Minimum required seeds/ha	14337	seeds/ha			
Minimum required seed rate	3.871	seeds/m			
Seeder input seed rate	4	seeds/m			
Spacing between seeds	25	cm			
Actual seed/ha	14815	seeds/ha			
Actual viable seed/ha	13778				
Actual expected stocking from seed	4133	stems/ha			
Required amount of seed and cost					
Weight of seed	0.0030	g/seed			
Weight of seed/ha	44.0	g/ha			
Net weight of seed required for block	2.2	kg			
Seed cost per hectare	$65.15	$/ha			
Initial Stand Establishment Cost					
Total seeding cost	$390.15	$/ha	Total planting cost (incl. site prep)	$900.00	$/ha
			Seedling cost	$360.00	$/ha
			Planting labour cost	$240.00	$/ha
Future Costs					
Fill planting cost	$0.00	$/ha	Fill planting cost	$0.00	$/ha
Juvenile spacing cost	$0.00	$/ha	Juvenile spacing cost	$0.00	$/ha
Total Costs (at Free-growing)					
Total cost of seeding at establishment	$390.15	$/ha	Total planting cost at establishment	$900.00	$/ha
Total cost of future stand est. (FV)	$0.00	$/ha	Total cost of future stand est. (FV)	$0.00	$/ha
Total cost of future stand est. (PV)	$0.00	$/ha	Total cost of future stand est. (PV)	$0.00	$/ha
Total cost of seeding to free-growing	$390.15	$/ha	Total cost of planting to free-growing	$900.00	$/ha
Difference of total cost (at free-growing) by choosing seeding			$509.85	$/ha	
			57%	% savings	

[7] Available to FPInnovations members upon request.

FPInnovations

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