IS DIRECT SEEDING A GOOD OPTION FOR REGENERATION IN BRITISH COLUMBIA?

by

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Abstract

In British Columbia, forest tenure holders have the obligation to reforest harvested areas, and the government invests in regeneration in areas damaged by wildfire or mountain pine beetle (MPB). Direct seeding (or direct sowing) is a process by which woodlands are established or re-established by sowing tree seeds at their final growing location. Direct seeding is being re-introduced in BC as an alternative to planting. Many factors affect the emergence and survival of seedlings, including temperature, precipitation, soil structure, predation and vegetation competition, all of which interact with the biological characteristics of the tree species. In field trials, site selection, site preparation, seed selection, vegetation control, increasing seeding density, sowing with alternate foods, and sowing with cover crop have been shown to improve seedling establishment. . However, the effectiveness of these techniques may vary with species, local environment, and location. Therefore, more research is needed before direct seeding can be applied broadly for regeneration in BC. Specific recommendations include: 1) more field trials; 2) enhanced communication and cooperation among research agencies and licencee holders; 3) modelling of germination response to varying conditions; 4) reduction in seed cost; and, 5) improvements in machine efficiency.

Key words: direct seeding, reforestation, forestry

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Introduction

Forestry is an important natural resource sector in British Columbia (BC), Canada, and timber harvesting contributes significantly to BC's economy. In order to achieve environmental, social, and economic targets and manage forests sustainably, the BC government has strict regulations on reforestation after logging. In recent years, severe forest fires and mountain pine beetle (MPB) infestations have posed serious reforestation challenges in BC (Hanson, 2015; Mitchell & Matute, 2015). From 2005 to 2015, the BC government has spent $348 million on *Forests for Tomorrow* program for reforestation activities. This program was launched in 2005 to reforest areas affected by wildfires and the MPB that would not be harvested and aimed to mitigate the effects caused by catastrophic wildfire and the MPB epidemic in the southern and central interior BC (BC government, 2016). Under the Forest and Range Practices Act (FRPA), forest licencee holders are obligated to reforest harvested areas and to meet free growing standards. Generally, a stand is free growing if it has reached specified stocking parameters (height, density, species composition, etc.) and is less susceptible to natural disturbances, including disease, browsing, drought, heat, and snow (B.C. Ministry of Forests, 2000). In general, it takes 10 to 20 years for the stand to produce a free-growing stand, depending on the species, and local climate and topography. Successful reforestation involves a series of silviculture activities, and one of them is regeneration.

The two most common methods used in BC for regeneration after clearcutting are natural regeneration and planting. Although sometimes there will be advance regeneration survived after clearcut logging, most successful natural regeneration is from seeds, and this requires three components: seed sources, suitable seedbed, and suitable environment. If these components are not satisfactory at a given location, site preparation or other silviculture activities would be needed to assist regeneration. Recently, fire and MPB have damaged significant area in BC. The BC Ministry of Forests, Lands and Natural Resource Operations estimates that the MPB has killed a cumulative total of 723 million cubic meters of timber, and the cumulative area of BC affected by MPB is estimated at 18.3 million hectares since 2001. When severe, these disturbances can reduce the local seed supply, hindering natural regeneration, and it can be costly to regenerate via planting. As a consequence, governments, forest licensees and researchers have started looking for alternative methods to reforest the land base.

Direct seeding (or direct sowing) is a process by which woodlands are established or re-established by sowing tree seeds at their final growing location. This technique has been practiced in Canada since 1900s, though is less used than planting. From 1900 to 1972, most direct seeding has been in Ontario and Alberta, and BC only accounted for about 5% of total area that was direct seeded in Canada (Figure 1; Waldron, 1973). Waldron (1973) summarized historic direct seeding activity in Canada from 1990 to 1972 and observed that, with the exception of Jack pine (*Pinus banksiana*), direct seeding has been a failure. However, with better understanding of ecology and silviculture, and improved operational practices, direct seeding may become a viable reforestation technique in BC and mitigate problems caused by wildfires and MPB.

Table 1 the area that was direct seeded in each province in Canada (from Waldron, 1973)

Province	Acreage (1900–72)	% (1900–72)	Year of 1st recorded seeding	Estimated acreage direct seeded in 1972
Ontario	139,392	41	1905	20,700
Alberta	122,725	36	1911	15,600
Quebec	27,227	8	1908	2,600
British Columbia	15,558	5	1923	2,100
Nova Scotia	10,037	3	1904	0
Manitoba	8,573	3	1904	300
Newfoundland	5,203	2	1950	0
New Brunswick	4,734	1	1923	300
Saskatchewan	3,529	1	1909	200
Prince Edward Island	0	0	—	0

The purpose of this essay is to provide a literature review of recent research on direct seeding in other countries, as well as in Canada, and to answer the following questions.

1. Where has direct seeding been used, and for what purposes?
2. What are the potential advantages of direct seeding over planting and natural regeneration?
3. What factors affect the success of direct seeding?
4. What silviculture techniques have been used to help improve outcomes, and what are their limitations?
5. Is direct seeding an option for reforestation in BC?

Following the literature review, I will integrate this information, discuss the limitations of past and current research, and identify potential knowledge gaps. Finally, I would provide some recommendations on what should be done in the future.

Literature Review

Who uses direct seeding

Harmer and Kerr (1955) have traced the origins of direct seeding in Europe back to the 14^{th} century. However, because of the problems associated with direct seeding, practitioners started forest nurseries in 17^{th} century (Willoughby, 2004). Since then, planting seedlings from nurseries has become more commonly used in reforestation. Recently, the theoretical potential advantages of direct seeding over planting, such as more rapid establishment, more natural appearance and lower cost, have led to renewed interest in this technique (Willoughby, 2004). Currently, direct seeding is used in afforestation on abandoned lands, ecosystem restoration, and reforestation after logging.

Direct seeding has been widely used to afforest abandoned lands around the world, including United Kingdom, Spain, and Canada (Bravi & Chapman, 2012; Willoughby, 2004). These abandoned lands, including agricultural lands and mining properties, are usually subject to a rapid invasion of highly competitive weed species once human activities cease (Willoughby *et al.*, 2004b). Consequently, it may take many years for the land to grow back to broad-leaved or mixed woodlands (Benjamin, Domon & Bouchard, 2005). In addition, tree recruitment on abandoned agriculture site is usually dominated by wind-dispersed species, rather than a broader mix of native species (Willoughby, 2004). Direct seeding can be a practical technique for creating a mixed woodland at lower cost (Willoughby & Jinks, 2009) and is used in Europe as a commercial system for woodland regeneration on agricultural lands (Watson, 1994, 1996).

With increasing land degradation rates in some sub-tropical and tropical regions, direct seeding can be a viable low-cost technique for forest rehabilitation on a broad scale (i.e. China, Australia, and Brazil) (Doust, Erskine & Lamb, 2008). In southern China, for example, seedlings of indigenous climax species are rare. This has limited the succession of plantations of early successional species toward natural forest conditions, reducing biodiversity and provision of ecosystem services (Wang, Ren, Yang & Li, 2011). Natural recovery in some ecosystems (e.g.

tropical forests) can be arrested or slow, taking up to 500 years (Kartawinata, 1994). In such cases, direct seeding is a useful method to add species diversity because of its low cost and speed.

Direct seeding has been used after logging or to modify monoculture forests in some European countries. For instance, in Finland it is being widely used for regeneration of Scots pine (*Pinus sylvestris* L.) after logging (Hypponen & Hallikainen, 2011). In central Europe, it has become a high priority to convert pure Norway spruce (*Picea abies*) stands into mixed stands over the last decade due to its sensitivity to abiotic and biotic stress factors (Ammer, Mosandl & Kateb, 2002; Kazda and Pichler, 1998). However, this silviculture technique is often constrained by limited budgets. As a result, direct seeding has been used to regenerate deciduous trees below the canopy of conifer stands, as it was proven to be a very economical method (Kankaanhuhta & Saksa, 2013).

Why direct seed?

Compared to planting seedlings, there are several advantages of direct seeding. One of them is its cost- and time-efficiency, especially for treating large amounts of area with high seeding densities (Eagle & Parrotta, 2001; Kinnunen, 2003; Sullivan, T.P. & Sullivan, D.S., 1984; Thomson, 2005; Wennstrom, Bergstem & Nilsson, 1999). For example, Walker's trials (Thomson, 2005) showed that directly seeded trees cost a total of approximately 18 cents each, whereas planting costs 13 cents per seedling, plus another 23 to 25 cents once planted. Engel and Parrotta's (2001) research also indicated that tree plantations may cost 1.5 to 2.5-times the cost of direct seeding, though different planting techniques and the presence of invasive grasses can influence the costs greatly. In addition, direct seeding has greater resource efficiency than other tree establishment methods (Eagle & Parrotta, 2001). Once a site has been properly prepared, seeding can be applied immediately (Thomson, 2005). The ability to plant seed quickly and to blanket an area when conditions are right, is a major advantage.

The low cost of seeds also allows the use of large quantities of seed, which could secure a high number of trees established after few years (Balandier, Frochot & Sourisseau, 2009). Heavy seeding may result in sufficient survival seedlings to stock the site that has been suffered from serious disease issues, such as pine rusts (Thomson, 2005). With some areas suffering up to 40% mortality, the cost of heavy seeding would be more reasonable than replanting. Besides, nurseries may not produce enough seedlings to meet the province's upcoming needs in stands destroyed by the MPB and other disease (Thomson, 2005).

Direct seeding is less labour-intensive than planting, as it usually only needs a few operators and mechanists to finish the job, whereas the production of planting is highly constrained by the number of available planters, and how fast they can cover the ground. Besides, in remote or challenging areas, it can be expensive to transport the planters, equipment, and supplies needed for planting. In addition, direct seeding can help reduce the risk of trees falling on forestry workers in beetle-infested stands.

Seed germination from direct seeding may have better adaptation to the environment, leading to potential better growth. Some research showed that seedlings from direct seeding may have better root development and better timber quality (Hanson, 2015). Furthermore, there are problems associated with using nursery stock that seedlings are getting shock from harsh conditions (Palma, Laurance & Marrs, 2015). In this case, regenerations from seeds may grow better than seedlings from the nursery.

Compared to natural regeneration, direct seeding has similar advantages as conventional planting. One of these advantages is that managers have better control on the characteristics of regenerated stands, including stand species composition, density, and spacing, and it is more likely to achieve their objectives. For example, in order to mitigate MPB problem, managers may want to decrease the proportion of pine in that stand and shift it to mixed-species stand. However, it may be hard to achieve if the stand was pine monoculture before the infestation.

The quality of seeds can be improved through artificial selection and preparation, and these strategies can influence seed emergence, survival, and growth rates. Through the BC provincial tree seed center, seeds can be tested and selected in orchard, and their quality can be improved through different programs in order to be better adapted to local conditions (BC Government, 2016). For stands that are destroyed by severe wildfire, where there are insufficient seed sources, direct seeding could provide enough seeds for regeneration (Hanson, 2015).

Factors affecting the success of direct seeding

There are many factors influencing the establishment of regeneration, and these factors can be categorized into two groups: abiotic factors and biotic factors. Abiotic factors are non-living components of an ecosystem, whereas biotic factors are living components of an ecosystem, such as animals and plants. However, the interactions among these factors are complex, and some of them are site-specific (Mitchell & Matute, 2015). In this case, the effects of these factors and conclusion of research trials may only applicable under certain circumstance. Appendix 1 summarized the basic information of direct seeding trails that are referenced in this essay.

Abiotic factors

Climate is one of the primary factors that affect the success of direct seeding. Temperature and precipitation are two indicators of climate. The combination of these would affect seedling in different stages. Successful seed germination requires suitable regeneration niches with favorable environment, including oxygen, chilling, heat and moisture, initially to overcome any dormancy, then to provide suitable conditions for embryo development. However, excessive heat or moisture at this stage can lead to death or secondary thermal dormancy (Jinks, Willoughby & Baker, 2006). Harsh climatic conditions could also cause post germination, meaning that seeds could remain dormancy for several years before germinate (Tillman-Sutela, 1995). After germination, young seedlings rapidly become autotrophic and dependent on surrounding microsite for light, heat, nutrients and water. This process of seedling emergence is a highly vulnerable stage of the regeneration process (Willoughby & Jinks, 2009). During this stage, moisture content would be very critical because roots are still too short to absorb moisture in deep soil. Seedling roots must extend downwards faster than the loss of water from the soil by evaporation (Willoughby & Jinks, 2009). In addition, soil surfaces exposed to direct solar radiation can experience very high temperatures, causing a significant proportion of tender young seedlings be killed if shoots do not rapidly grow away from the soil/air interface (Smith, Larson, Kelty & Ashton, 1997). In other cases, temperature may get too cold, which may kill seedlings as well. Cold air will drain in the evening and cause damage to the foliage and buds near surface of the ground.

Unsuitable seedbeds, including thick humus layer and stoniness can negatively affect seedling establishment (Hypponen & Hallikainen, 2011). Other chemical and physical characteristics of soil, such as nutrient and moisture content, density, horizons, and texture, would affect a series of root activities and the growth of seedlings. Field research indicates that mesic soil with mineral seedbed may be best for seed germination for most situations (Mitchell & Matute, 2015).

Biotic factors

There are mainly three main biotic factors that would affect the success of direct seeding: predators, competing vegetation, and the biological characteristics of seeds. Predation of seeds and shoots can be caused by insects, birds, rodents, and other small mammals. In the Northeastern United States, Gill and Marks (1991) showed that seedling mortality was essentially due to predation by voles rather than herbaceous competition and that predation was more serious under herb cover. Vegetation cover, in fact, increases the probability of seedling damage caused by small rodents, because it decreases the risk of small mammals being seen by their predators (Ostfeld & Canham, 1993).

In addition to small rodents, invertebrates can be another threat to seeds. In tropical and Australian regions, for example, researchers observed that invertebrates, such as ants, contribute a lot to seed loss (Anderson, 1987; Garcia-Orth & Martinez-Ramos, 2008; Woods & Elliott, 2004). Anderson (1987) showed that ants removed 93% of *Eucalyptus baxteri* seeds and 58% of *Casuarina pusilla* seeds in an Australian woodland. In Mexico, more than 90% of small-seeded, early successional species were predated by invertebrates (Garcia-Orth & Martinez-Ramos, 2008). In addition, the level of losses can be fluctuated, which is influenced by the population of rodents in that area and the availability of alternative food sources. Moreover, shoots and leaves of seedling may also be browsed by animals, especially during winter time, when there is often food shortage. Depending on the availability of alternative food, animals may only affect small portion of leaves and shoots, or they may eat the bark, which would cause more damage and even mortality. Although animal browsing is a problem to seedlings during all stages, it could be more lethal to younger seedlings.

Another biotic factor is surrounding vegetation, which can have both beneficial and negative effects on the regeneration by modifying site resources and microclimate. This vegetation can play an important role during early emergence stages of seedlings. For instance, shrubs and herbs may protect seeds from predators, and deter browsing and provide food source for animals (Watson, 1994). Moreover, the vegetation can provide protection against frost, high temperatures and high transpiration (Balandier *et al.*, 2009), and these are especially important for young germinates and seedlings, which are highly vulnerable to heat stress and moisture loss (Willoughby & Jinks, 2009).

On the other hand, shrubs and herbs can compete with seedlings for water, nutrients, space, and lights, especially on fertile, ex-agricultural site, and they have negative effects on seedling growth (Doust *et al*., 2008; Willoughby, Jinks, Kerr & Gosling, 2004a). Different plant species have different abilities to collect and utilize resources. In general, grasses have more negative effects and are stronger competitors than herbs (Gomez-Aparicio, 2009). These competition species usually grow very quickly and occupy the stand completely, putting greater threats to shade-intolerant species. Furthermore, seedlings would grow very slow due to high competition, and it leads to longer young stage, which in return, put them under risks from other factors. In the studies conducted by de Steven (1991), even if herbaceous cover had a positive effect on the emergence of species, it had negative impacts on seeding survival and growth of all five species tested. In dry conditions, grassland vegetation considerably reduces soil water, increasing the intensity of competition and, thus, decreasing seedling survival, whereas in wet conditions, herbaceous vegetation has a smaller effect on seedling survival (Davis *et al*., 1999).

Biological characteristics of species, including seed size, growth rate potential and light requirement, would affect the success of regeneration, and seed size may be one of the most important factors among them. Experiments (Doust *et al*., 2006, 2008; St-Denis, Messier & Kneeshaw, 2013; Wang *et al*. 2011; Willoughby *et al*., 2004a) indicated that there is a better survival for large seeds than for small seeds, as the large nutrient reserves and energy stock in their acorns and their ability to rapidly develop a long taproot allow young seedlings to survive short periods of drought or other stresses. Thus, species with larger seeds may be less immediately dependent on the surrounding environment for moisture, light and nutrients during critical emergence phases than smaller seeded species (Kimmins, 2004). As a result, larger seeded species can be better adapted to direct seeding systems where conditions in the immediate emergence phase are limiting (Willoughby *et al.*, 2004b). Sometimes, seed size may be the primary factors influencing seed survival and germination rates.

Techniques to improve outcomes

There are several techniques that may help improve the germination rate and survival rate, and increase the chance of reaching free growing standard, though different factors may interact with each other and make situations complicated. First of all, site selection and site preparation is important to successful establishment. Since the 1990s, the majority of direct seeding in Finland has been carried out mechanically in connection with site preparation (Hypponen, 2000). There are different site preparation techniques for different site conditions and usually combined with specific sowing methods. In peatland forests, for example, soil scarification and scalping is required because of the thick layer of raw humus (poorly decomposed residues of feather mosses), which gradually develops on the top of the peat layer following drainage (Helenius & Saarinen, 2013). Heavy machine, such as excavator-mounted rototiller, may be good for soil scarification in peatlands, improving the moisture conditions of the seedbed by mixing the ground vegetation, raw humus layer, and peat (Helenius & Saarinen, 2013). Other machines, such as disc-trencher with simultaneous seeding, are helpful in preparing suitable microsite. Past work on direct seeding in forestry has been concerned with seed spot microsites concluding that exposed mineral soil is best for most species (Riley, 1980). Their work demonstrated that subtle changes in the physical attributes of the seed spot microsite can have a considerable impact on seedling emergence. Different positions within the scalps created by the scarifier have different moisture characteristics depending on weather and site conditions (Van Damme & Bax, l991). The scalp base is wettest and may flood, while the sloping berm is prone to drought. As a compromise in moisture regimes, the mid-slope region of the scalp was chosen for seed drop (Van Damme & Bax, 1991). For aerial- or ground-broadcast seeding, controlled burning is usually used as a site preparation method to remove litters and expose mineral soil for seeds.

Direct seeding can also be combined with other post-emergence applications to get better results. One of them is vegetation management, which can reduce the competition on resources, and increase survival rates of seedling. According to Willoughby & Jinks (2009), weeding using selective herbicide can improve survival by up to 50% and growth rate by up to 80% for deciduous species. They also suggest that weeding would achieve best results if it is applied for the first 3 years. By increasing growth rate, it can reduce the time during which trees are susceptible to damage from a wide range of other biotic factors. (Willoughby & Jinks, 2009). However, weed control usually improve the survival rates and growth rates, but in some cases it may have no significant effect on it (St-Denis *et al.*, 2013). There is currently a great deal of pressure to reduce the environmental impacts of vegetation control, particularly herbicide in forests (Willoughby *et al*., 2009).

One alternative to vegetation control is seeding with cover plants, which can also protect the tree seedlings from extremes of temperature, sun scorch, frost damage, drying winds, and water run-off encountered on bare soil, as well as to discourage mammal damage and reduce weed growth (Watson, 1994; Balandier *et al*., 2009). Cereals and rye (*Secale cereal* L.) have been used in direct seeding mixes with oak and pine seeds (Cotta, 1822), and blue lupin (*Lupinus perennis* L.) has been used in Germany to foster tree establishment in poor soil (Reineche, 2000). However, at the present cover crop technique is relatively little used and the results reported are contentious (Balandier *et al*., 2009). The actual efficiency of a plant cover and its dynamic ability to prevent weed development and promote tree seedling establishment needs further study. For example, vegetation cover may have beneficial effect on predation prevention by hiding seeds from sight of predators like bird, but it also can be negative by offering rodents protection from bird of prey (Balandier *et al*., 2009).

Artificial seed selection and seed preparation is another important technique. For example, the use of seeds with high germinative capacity can make a significant difference on emergence rates (Wennstrom *et al.,* 1999). In addition, it is cheaper to achieve a stocking density of 10 000 stems/ha and to rely on a high initial seedling density to try to overcome the pressures of browsing and weed competition (Watson, 1994, 1996). Mixing tree seeds with alternative food source is another way to reduce predation of seeds. Field research showed that the direct seeding of Douglas-fir and lodgepole pine with sunflower and oat seeds has greatly increase the survival of conifer seeds from predation of rodents, especially for seeding in fall (Sullivan, T.P. & Sullivan, D.S., 1984).

A good of control of timing of sowing may also improve the seed emergence and survival rates (Hypponen & Hallikainen, 2011). Table 2 (Waldron, 1973) shows the summary of sowing season in Canada from 1900 to 1972. Depending on the location and climate of that area, direct seeding could occur during anytime of the year. However, spring and early summer have been regarded as the biologically best direct seeding dates for many species, such as Scots pine. Sometimes, the site preparation and seeding machinery cannot be used on a regeneration area until soil frost has melted, the soil has drained, and its carrying capacity has improved sufficiently, causing the recommended direct seeding season in the spring and early summer very short for mechanical seeding (Hypponen & Hallikainen, 2011). Therefore, autumn can also be a reasonable period for direct seeding of pine in Finland (Hypponen & Hallikainen, 2011), and seeds will go through stratification naturally during winter. Compared to spring and autumn, the success of summer seeding has generally produced the most unsatisfactory results because of the heat and drought (Kinnunen, 2003).

Table 2 Summary of sowing season in Canada (from Waldron, 1973)

Season of sowing	Acreage (1900–72)	%
Spring (Apr.-May)	55,324	16
Summer (June-Aug.)	15,244	5
Autumn (Sept.-Nov.)	222,550	66
Winter (Dec.-Mar.)	43,860	13

Discussion

Based on the summary of direct seeding trials (also see Appendix 1), I think direct seeding may be an option for reforestation in BC where natural regeneration and conventional planting are not expected to achieve target stands at reasonable cost. The decision key (Appendix 2) for reforestation strategies in BC integrates additional factors that are need to be considered. However, before it can be applied at a larger scale, there are still some questions need to be addressed. First of all, although many research trials indicated that direct seeding can be cheaper than planting, most of them only included the costs of early-stage silviculture activities, such as sowing, planting, and site preparation, and did not include the additional costs of monitoring and surveys. These initial establishment costs serve as important guidelines; however, the post-planting site maintenance costs need to be clarified. In particular, how different planting can influence the cost of site maintenance should be compared to direct seeding (Palma *et al*., 2015). The survival rate of seedlings after direct seeding may be acceptable, but it may take a long time to reach free growing stand. In this case, additional silviculture activities, such as brushing and fill-planting may be needed, which can increase the total costs significantly. In addition, few research has linked the risk of failure of direct seeding to the potential financial losses, which is an important consideration to forest tenure holders.

There is insufficient understanding about the complex interaction of different factors that affecting the result of direct seeding. According to Palma et al.'s (2015) review of over 120 peer-reviewed papers of direct seeding, only half of their experiments reported the direct causes of death. Without a clear understanding of causes of death, it would be hard to improve the technique. Moreover, even though the results indicate that direct seeding can be a viable establishment method, the identity of species to be used, the circumstances under which they should be directly sown and the most appropriate timing of sowing will vary with situations (Doust *et al*., 2008). The fundamental differences in the ecological characteristics of the areas and the types of species used make the direct transfer of the methods and guidelines that have been developed problematic (Vanderwoude, Pickersgill & Dickinson, 1996). Seedling establishment after artificial seeding is greatly affected by the plant community and seed identity, and the requirements for seedling recruitment are always species-specific within the same community (Wang *et al*., 2011).

Some trial results are inconsistent with each other due to the variation in environment, species used, and other factors, and these could lead to confusion to other practitioners. For example, some research showed that crop cover is beneficial to seedling establishment; however, others indicated that it has no effect or even negative effects on seedling survival (Balandier *et al*., 2009). Wang *et al*. (2011) found that conditions that favored seedling emergence often differed from those that favored seedling survival. For example, understory vegetation and litter did not influence the final seedling establishment, but it will affect the seedling growth. The result of different soil scarification methods in forest regeneration also vary a lot in peatlands because of the complex interactions of the depth of the water table, the thickness of the raw humus layer, the composition of ground vegetation, and the weather conditions (Helenius & Sarrinen, 2013).

The long-term monitoring results (5 to 10 years) of direct seeding trials are lacking in most research. This information may be important to understand the emergence patterns, emergence percentage, early growth patterns, and affecting factors. Many observations from northern Fennoscandia suggest that a pine seed can survive in the surface layers of soil for several years (Hypponen & Hallikainen, 2011). This pattern (so-called post germination) seems to be connected with the weather conditions of the growing seasons and the stratification of the seed, and it may play a significant role in forest regeneration under harsh climatic conditions (Tillman-Sutela, 1995).

Recommendations

Direct seeding has a potential to be an option for reforestation in BC, but there is more work need to be done in the future. More field trials need to be established in BC, involving different locations, species, and site preparation techniques, and long-term monitoring. Even though we can learn a lot from experiments in other places, sometimes the direct transfer of techniques and guidelines does not work due to the variation in each situation. Moreover, communications and cooperation among different research agencies and licencee holders should be enhanced, so that people can share information and learn from each other. In addition, a modelling approach can be used to model the germination response to varying environmental, climatic and stand conditions when direct seeding is carried out. By doing this, it may be possible to find out the importance of different factors and how do they interact with each other. Finally, more research should be done on improving machine efficiency and decreasing seed costs, so that the general cost of direct seeding would be lower, making this advantage more competitive.

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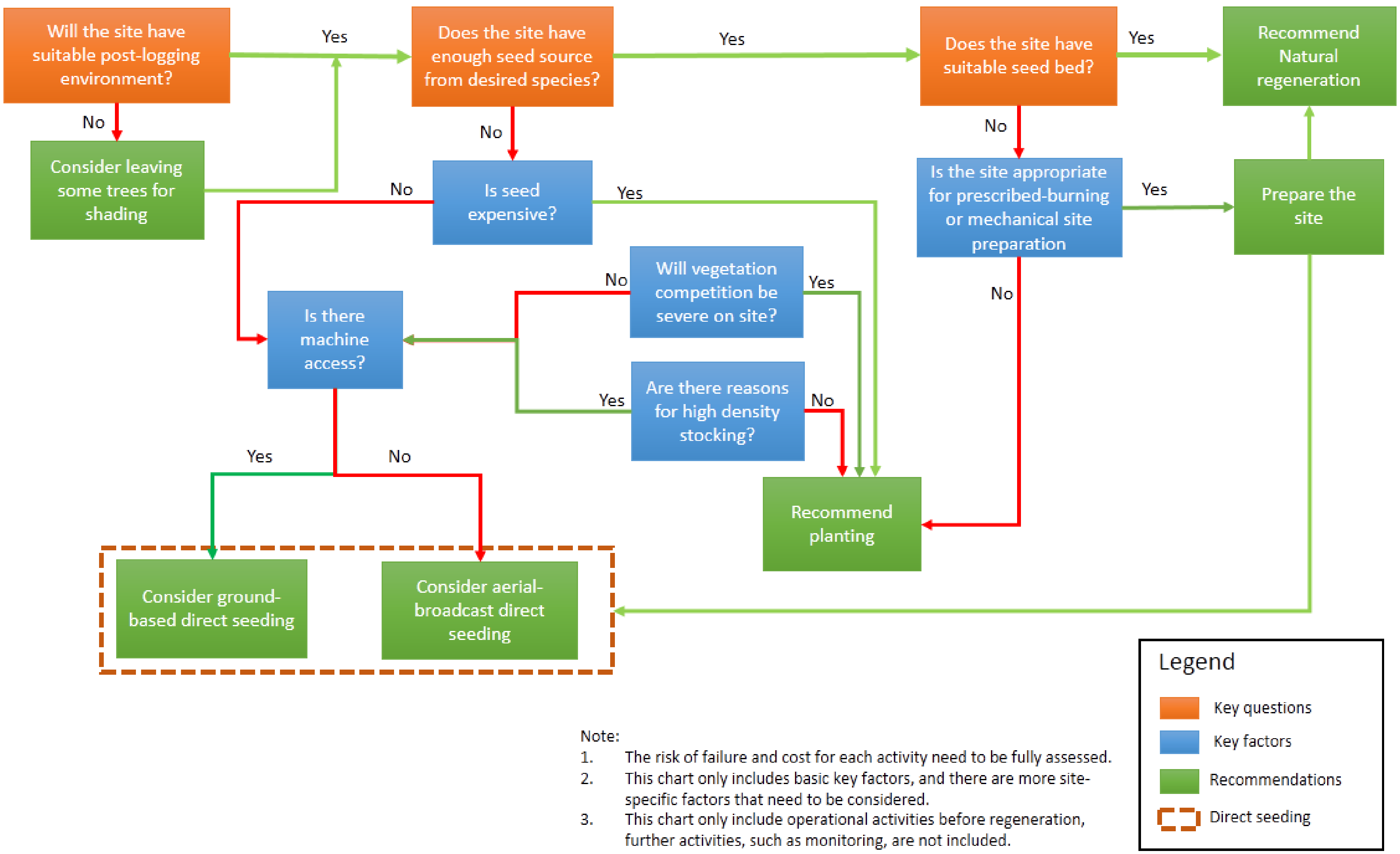
Appendix 1 Summary of Major Direct Seeding Trials Referenced

Author	Date	Location	Ecosystem	Target species	Treatment	Results/Conclusion
Balandier, Frochot & Sourisseau	2009	Central France	Formerly meadow, mainly used as pasture; temperate climate	Thorny shrubs, fruit trees, forest trees (mixture of several species)	Tested in bare soil, flora of the meadow, and two mixture of cover plants	Bare soil has the best result; meadow site has the lowest; the cover pant mixtures have the intermediate result.
Doust, Erskine & Lamb	2006	East Queensland, Australia	Wet tropical region; degraded sites	Rainforest tree species (more than 20 species tested)	Sowing at the beginning and end of the wet season	Two years after sowing: sowing time has little effect on seedling establishment; large seeds have more consistency; weed competition can negatively affect the establishment; establishment is related to successional status
Hyppönen & Hallikainen	2011	Finland	Boreal forest	Scots pine	Sowing in late autumn	Late autumn can be a reasonable alternative period for direct seeding, and more experimental research is needed
Helenius & Saarinen	2013	Finland	Forestry-drained peatland	Scots pine	Excavator-mounted rototiller for soil scarification	After 2 growing season, rototilling offered no advantage over scalping in terms of the number of established seedlings or seedling height
Kankaanhuhta & Saksa	2013	Southern Finland	Privately owned forests	Norway spruce and Scots pine	Planting Norway spruce and direct seed Scots Pine	Record 3-year-old planting and 4-year-old direct seeding areas; for planting, the costs were weakly related to quality; for direct seeding, there is a significant positive correlation between the cost and number of pine seedlings.
St-Denis, Messier & Kneeshaw	2013	Quebec, Canada	Abandoned agriculture fields with humid continental climate	Yellow birch, paper birch, tamarack, sugar maple, northern red oak, and red pine	To test the effects of seed characteristics, environmental conditions, competition and predation	Only large seeded species should be used for forest restoration in this region
Sullivan & Sullivan	1984	British Columbia, Canada	Coastal western hemlock biogeoclimatic zone and interior Douglas-fir biogeoclimatic zone	Douglas-fir and Lodgepole pine	Sowing with alternative foods	Seed predation from birds and rodents was greatly reduced when swing with alternative foods.
Van Damme & Bax	1991	Ontario, Canada	Mixed boreal forest	Jack pine	To test the effectiveness of seed delivery techniques	The development of a pneumatic seeder, a compacting wheel and an improved plastic seed shelter tool are good for better seed germinant
Wang, Ren, Yang & Li	2010	South China	four plantations: eucalyptus, mixed-native, mixed-legume, mixed-conifer	*Castanopsis chinensis*, *Cryptocarya chinensis*, *Psychotria rubra*	understory vegetation and litter retained or removed	Larger seeds have better emergence and growth; the removal of understory vegetation and litter have little impact on the final seedling establishments, but did influence growth of seedlings.
Wennstrom, Bergsten & Nilsson	1999	Northern Sweden	Boreal forest	Scots pine	To test effects of seed origin, and microsite preparation	Orchard seeds have higher seedling emergence and higher height growth than stand seeds; microsite preparation can reduce the number of seeds used to achieve certain stocking standards.
Willoughby	2004	United Kingdom	Afforestation on reclaimed and ex-agricultural land	Sessile oak, Scots pine, ash, and Sycamore maple	Sowing with agricultural cover crop with/without weed control	Protection and weeding is important when using direct seeding; no benefits from established cover crops or relying on naturally occurring vegetation
Willoughby & Jinks	2009	United Kingdom	Native broadleaved woodland in lowland Britain	Deciduous species (i.e. ash, cherry, field maple, oak, etc.)	The duration of vegetation management	Weeding for 1 year gave a significant benefit to overall survival, but weeding for 3 years gave the most improvement to survival and growth of the remaining trees.

Appendix 2 The Decision Key for Regeneration in BC



Note:

1. The risk of failure and cost for each activity need to be fully assessed.
2. This chart only includes basic key factors, and there are more site-specific factors that need to be considered.
3. This chart only include operational activities before regeneration, further activities, such as monitoring, are not included.