Direct seeding of boreal conifers on freely drained andosols in Southern Iceland

JÓN GEIR PÉTURSSON [1]

AND

ADALSTEINN SIGURGEIRSSON [2]

[1]*The Icelandic Forestry Association, Ránargata 18, IS-101 Reykjavik, Iceland*
E-mail: jgp@skog.is

[2]*Icelandic Forest Research, Mógilsá, IS-116 Reykjavik, Iceland*
E-mail: adalsteinn@skogur.is

SUMMARY

The success of a direct seeding trial in southern Iceland was evaluated throughout four growing seasons. The trial involved comparison of the three coniferous species most commonly used in Icelandic forestry lodgepole pine (*Pinus contorta* Dougl. var. *contorta*), Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and Siberian larch (*Larix sibirica* Ledeb.) and five seeding methods: (1) control, (2) plastic cone, (3) pyramidal indentations, (4) cover with gravel and (5) cover with pumice. For comparison, one-year old seedlings were planted in the spring and autumn. The seedling emergence for all species and seeding methods was 11.3% after the first summer and 19.0% after the second. Seedling emergence was significantly higher for lodgepole pine (41.3%) than for Sitka spruce (26.8%) and Siberian larch (22.6%). Sowing under a plastic cone gave the highest seedling emergence or an average of 50.3% for all species. Seedling mortality was high after the first winter, except under the cones, where more than 80% of the seedlings survived. After three winters the highest survival was found for lodgepole pine, where 19.7% of the viable seed yielded established seedlings, compared to 10.9% for Siberian larch and 9.2% for Sitka spruce. The number of seeding spots having at least one live seedling after three growing seasons ranged from 50 to 76% for lodgepole pine, 2.5 to 45% for Sitka spruce and 6.6 to 40% for Siberian larch. Survival of planted seedlings differed between planting seasons, with spring planting yielding better survival for Sitka spruce and lodgepole pine and autumn planting for Siberian larch. Lodgepole pine gave the most promising results for establishment by direct seeding. From the fourth year establishment ratios, it can be concluded that the use of plastic cone-shelters is the most promising method of direct seeding and appears to provide establishment success comparable with planting.

Key words: afforestation, conifers, direct seeding, Iceland, seedling emergence, seed predation

YFIRLIT

Bein sáning á fræi þriggja barrtrjártegunda í útjörð á Suðurlandi

Tilraun var komið á fót vorið 1993 með beinar sáningar á barrtrjáfræi að Mosfelli í Grímsnesi og var hún metin við lok fjórða sumars frá upphafi tilraunar (árið 1996). Í tilrauninni var borinn saman árangur af sáningu stafafuru-, sitkagrenis- og rússalerkifræs með fimm mismunandi sáningaraðferðum, og auk þess árangur af gróðursetningu ársgamalla plantna sömu tegunda, að vori og hausti. Meðalspírun allra tegunda við lok fyrsta sumars (1993) var 11,3% en 19,0% við lok annars sumars (1994). Bein sáning stafafurufræs gaf hæstu heildarspírun (41,3%, án tillits til sáningaraðferðar), marktækt hærri en fyrir sitkagreni (26,8%) og rússalerki (22,6%). Sáning með plastkeilum gaf besta spírun trjáfræs (50,3%, fyrir allar þrjár tegundir). Afföll fyrsta vetur tilraunarinnar urðu minnstar hjá ungplöntum sem sáð hafði verið til undir keilum (80% lifun). Eftir þrjá vetur reyndust afföll smáplantna minnst hjá stafafuru, þar sem sáning leiddi til plöntumyndunar (þriggja ára, lifandi fræplöntu) í 19,7% tilvika, samanborið við 10,9% hjá rússalerki og 9,2% hjá sitkagreni. Fjöldi sáningarstaða þar sem var að finna lifandi trjáplöntu við lok fjórða sumars frá upphafi tilraunar var á bilinu 50-76% hjá stafafuru, 2,5-45% hjá sitkagreni og 6,6-40% hjá rússalerki. Gróðursetning að vorlagi leiddi af sér minnst afföll hjá stafafuru og sitkagreni, en hjá rússalerki voru afföll minni hjá trjáplöntum sem gróðursettar höfðu verið að haustlagi. Bein sáning virðist einkar efnileg og áhugaverð aðferð við nýskógrækt á stafafuru á rýru landi. Árangur af notkun beinna sáninga við nýskógrækt virðist best tryggður með notkun plastkeila, en með þeirri aðferð má fyrir minni kostnað ná sambærilegum árangri og með gróðursetningu trjáplantna.

INTRODUCTION

Iceland has proportionally the smallest area of forest in Europe, with less than 1.4% of the land area covered by forests or woodlands. Eleven centuries of settlement, with concurrent deforestation and overgrazing, have resulted in the loss of 95% of the pre-settlement forest cover and widespread land degradation and soil erosion (Arnalds 1987). Afforestation is considered to offer an effective means for land rehabilitation and protection against erosion. Hence there is a great interest in developing cost-effective afforestation methods.

Direct seeding of conifers has been used for forest regeneration in high latitude countries for a long time (from Ström 1830, in Hagner 1990), and it is still widely used in the boreal forest zone of Europe and North America (Winsa 1995, Nilson & Hjältén 2003). During the past few decades, afforestation in Iceland has mainly involved planting exotic conifers, especially Sitka spruce (*Picea sitchensis* (Bong.) Carr.), lodgepole pine (*Pinus contorta* Dougl. var. *contorta*) and Siberian larch (*Larix sibirica* Ledeb.) (Blöndal *et al*. 1986). Direct seeding of these species has not been practiced, mainly because of the limited quantity and high prices of imported seed of suitable origin. However, seed supply conditions are improving and exotic species have started to seed abundantly in older plantations (Pétursson 1995, Pétursson & Sigurgeirsson 1997). Hence, in order to determine whether direct seeding can be efficiently used for afforesting extensive areas, there is a need for quantitative data on seedling establishment resulting from direct seeding of the most used conifer species in Iceland.

Afforestation has increased considerably in Iceland during the last decade. Tree planting, using native and exotic species, began over a century ago but at a very low level until the early 1990s, thus explaining the low weighted mean age (17 years) of planted forests in Iceland (Sigurdsson & Snorrason 2001). Large-scale country-wide afforestation programs have been established which provide grants to various parties for multiple-use afforestation goals. This has resulted in a five-fold annual increase in the number of planted tree seedlings in the last decade (Pétursson 1999). Lodgepole pine and Siberian larch have been among the most promising tree species for reclaiming heavily eroded and degraded areas (Blöndal 2001). These are areas where organic capillary breaking material is often gone owing to soil erosion and which provide promising sites for direct seeding as a regeneration method.

The main advantages of direct seeding compared with planting are that it can be simpler to perform and less expensive (Wennström *et al*. 1999), especially when nursery facilities are limiting or non-existent (Putman & Zasada 1986). Another important advantage is that plants established from direct seeding may develop more stable root systems and better stem quality than plants established from planting (Graber 1988). This is especially relevant for lodgepole pine, where instability, toppling and basal sweep owing to abnormal root formation are common problems in plantations (Burdett *et* *al*. 1986, Sigurgeirsson 1988, Rosvall 1994). The disadvantages of direct seeding can however include inefficient use of limited amounts of expensive seeds and a lack of control over environmental conditions that affect germination and seedling establishment, giving variable results (Putman & Zasada 1986).

Scarification is considered advantageous for direct seeding and is usually necessary to obtain satisfactory results. Otherwise, germination is hampered as the seeds are separated from the mineral soil by organic material unable to transport capillary water (Hagner 1990).

Several sowing methods have been described to obtain better results. Making pyramidal indentations in the soil as a microsite preparation for direct seeding showed good results for Scots pine (*Pinus sylvestris* L.) in Sweden after disk-harrow scarification (Bergsten 1988) and after scarification with a rotating miller (Winsa 1995). The uses of different materials for covering the seeds have been considered conducive to improving seedling emergence and survival (Nilson & Hjältén 2003). The use of artificial plastic shelters over the seeds, has shown good results for a number of tree species at northern latitudes in, e.g. Finland, Sweden, Alaska, Canada and Norway (Lähde & Tuohisaari 1976, Sahlén 1984, Putman & Zasada 1986, Dominy & Wood 1986, Bergan & Eide 1988). Their function is to increase the air humidity and the temperature of both air and soil to levels more favourable for germination of the seeds and establishment of the seedlings (Lähde & Tuohisaari 1976). Another important advantage of the plastic cones is to protect the seeds from predators (Bergman & Bergsten 1984).

Direct seeding has not been practiced in Iceland to date as a method of afforestation with introduced conifers. To our knowledge this study represents the first study of its kind in Iceland. A summary of the results of this study has previously been reported by us in a popular journal aimed at end-users, Icelandic forest managers (Pétursson & Sigurgeirsson 1997). The objectives of the current study were; (1) to investigate the possibility of using direct seeding to establish conifer species as a method for afforestation in the cool climate of Iceland and (2) to compare different techniques for direct seeding of the different species. Three conifers commonly used in afforestation in Iceland and five different direct seeding methods were compared. In addition one-year-old seedlings were planted in the spring and autumn for comparison. The results after four growing seasons are presented.

MATERIALS AND METHODS

Study area

The trials were laid out at Mosfell in South

Table 1. Meterological observations from the nearest local weather station, Hæll in Gnúpverjahreppur, South Iceland (64°04'N; 20°15'V; 121 m a.s.l.) during the germination period (data obtained from the Icelandic Metereological Institute, unpublished data).

	Mean 1970 - 1992	**Year 1993**	**Year 1994**
Mean precipitation, Jun., Jul., Aug. (mm)	93.8	73.5	71.4
Mean precipitation, year (mm)	1153.0 ± 184.0	1194.9	1059,9
Mean temperature, Jun., Jul., Aug. (°C)	9.9	9.3	10.0
Mean temperature, year (°C)	3.5 ± 0.6	3.8	3.5
Mean max. temperature Jun., Jul., Aug. (°C)	13.6	14.1	13.8
Mean min. temperature Jun., Jul., Aug. (°C)	6.8	10	5
Mean snow cover in April (%)	31.7 ± 22.1	38	38
Mean snow cover in May (%)	4.7 ± 6.9	0	0
Mean wind speed, Jun., Jul., Aug. (knots)	6.8	9.3	6.8

Table 2. Seed origins and type of planting stock used in the trials.

				Seed material			Planting stock	
Species	**Provenance**	**Seed-lot no.1**	**1000-seed weight**	**Germ. May ´93[2]**	**Germ. Oct. ´93[3]**	**Container type**	**Age, spring [4]**	**Age, autumn [5]**
Siberian larch	Imatra	920007	12.05 g	52 %	34 %	fp 60	1/0	from spring
Lodgepole pine	Taraldsøy	910018	3.65 g	86 %	84 %	fp 67	1/0	from spring
Sitka spruce	Tumastadir	910035	2.98 g	86 %	88 %	fp 67	1/0	from spring

1 Seed identification number from the Icelandic Forest Research seed collection system.
2 Test without stratification.
3 Test 6 months after stratification.
4 Age of the seedlings planted in June 1993 (1-year old containerized seedlings). 5 Age of the seedlings planted in October 1993.

Iceland (64°08'N; 20°40'W; 70 m a.s.l.). The terrain is flat and is exposed to winds from all directions. The soils on the experimental site are freely drained andosols, with a pH of 5.6 to 6.3, carbon content of 4.6 to 11.4% and very low amounts of available nitrogen and phosphorus (Óskarsson *et al*. 1997). The vegetation is a moss heath dominated by moss species (*Rachomitrium* spp.) and several species of dwarf shrubs (see Óskarsson *et al*. 1997). The area was deforested centuries ago and used for grazing livestock until 1989.

Seed/Site preparation and design

The seedlots of Siberian larch, lodgepole pine and Sitka spruce were cold-stratified for two weeks before sowing, and the seeds subjected to a germination test, under laboratory conditions, to assess viability (Table 2). The experiment was established in four completely-randomised blocks. Each block included three tree species, using five different seeding methods and two planting methods. Within each replication there were 20 sowing (or planting) spots (see Pétursson 1995).

In the field, all sowing and planting spots were scarified beforehand, using a clearing saw equipped with a rototiller head (Eco-cultivator) that removed organic, capillary breaking material. The sowing (planting) spots were placed on the side of the hummocks as recommended for planting by Aradóttir & Magnússon (1992). The seed was sown less than two weeks later, in the first week of June 1993. Five different sowing methods were used: control, plastic cone, pyramidal indentations, cover with gravel and cover with pumice (see Table 3 for further details).

The number of viable seeds on each sowing spot necessary to obtain satisfactory stocking for conifers in Sweden has been estimated as 18.5 seeds/spot, where germination is 100%

Table 3. Description of the seeding methods used in the trials on the scarified seed spots.

Method	**Description1**
Control	Sown directly
Covered with gravel	Seeds covered with approx. 27 cm3 of gravel having diameter from 0.3 – 0.8 cm
Covered with pumice	Seeds covered with approx. 27 cm3 of pumice having diameter from 0.1 - 1 cm
Plastic cone	Cone model "Cercon", 80 mm high, bottom diam. 59 mm and top diam. 17 mm
Pyramidal indentation	Tool consisting of 10 pyramids, turned upside down, with base 4x4 cm and height 2cm, put together in two rows with 5 in each (see Bergsten 1988)

(1 See further descriptions in Pétursson 1995)

Table 4. Number of seeds sown on each spot.

	Methods		
Species	Control, covered with Gravel and pumice	Plastic cone	Pyramidal indentation
Sitka spruce and lodgepole pine	29	7	23
Siberian larch	48	12	39

(Hagner 1990). The number of viable seeds can be reduced to 4-8 per cone when sowing under the shelters (Saksa & Lähde 1982, Sahlén 1984, Dominy & Wood 1986), and when sowing in the pyramidal indentations, the number of seeds used can also be reduced (Winsa 1995).

As there is no experience of direct seeding of conifers under the harsh Icelandic climatic conditions, it was decided to increase the recommended number of viable seeds (Table 4). The recommended number of seeds on each spot was adjusted according to the germination of the species.

Seedlings were planted at two different planting times, spring and autumn (Table 2), using the same ground preparation as for the sowings.

Inventories and analyses

The trials were assessed regularly during the period 1993-1996. During the summer of 1993 (the first year of the experiment) emerged seedlings were counted in mid-July and late August. During the summer of 1994 the trials were assessed three times. The first assessment took place in early June, when the number of living seedlings from 1993 were counted. In addition an estimation was made of the mortality of the seedlings that had germinated in the previous year. Some of the seed sown in the spring of 1993 did not germinate until one year later. The second 1994 inventory took place in mid-July when the number of seedlings that had emerged in 1993 and 1994 were counted. The last inventory was made in late August, after germination had completed. In 1995 the trials were assessed in September, when estimation was made of the number of established seedlings. The last inventory was made in mid-June 1996 when the established seedlings were counted. The means for seedling emergence, seedling establishment, number of spots with at least one living seedling and survival were compared using ANOVA. To meet assumptions of normality and variance homogeneity, all percentage data were arc-sin transformed (Zar 1984). The significance of mean differences between methods and species was tested using Tukey's HSD test, where ANOVA indicated a difference at the 95% level. (Bishop & Lentner 1986, p. 167). The seeds were recorded as germinated if the emerging radicle was longer than the seed coat. Germination was calculated as the percentage of viable seeds sown. Seedling establishment ratios were calculated as the number of surviving seedlings/viable seeds sown.

RESULTS

Seedling emergence

After the first summer, 11.3% of the sown seeds had germinated. During the second summer, the germination increased by 18.9% of the remaining seeds, resulting in a total germination of 30.3% for all the methods and species used in the experiment. No further germination was observed after the second summer. Among species, the seedling emergence was significantly highest for lodgepole pine (41.3%). The methods of pyramidal indentations and pumice gave the best results after one growing season and were significantly higher than the control or cone and gravel. During the second summer, seedling emergence under the plastic cone was significantly highest. When the results from the

Table 5. Means and standard errors (SE) of the seedling emergence results for 1993, 1994 and total, with the statistical comparisons. Seedling emergence calculated as percentage (%) of viable seeds sown. The values with a different letter differ significantly (Tukeys HSD test, P<0.05). The small letters apply within species and the capitals are used to compare between species.

	Tree species										
	Pinus contorta	SE		Picea sitchensis	SE		Larix sibirica	SE		Mean	
Method	Year 1993										
Cone	12.5	4.6	a	11.5	2.5	bc	13.3	2.4	B	12.4	b
Control	2.5	1.6	ab	5.4	2.2	bc	5.2	2.4	B	4.4	b
Gravel	2.6	1.1	b	2.6	1.2	c	9.0	1.5	B	4.7	b
Pumice	11.4	4.7	ab	15.8	4.6	ab	19.3	5.9	Ab	15.5	a
Pyr. ind.	10.3	4.9	ab	9.6	3.6	bc	37.6	12.5	A	19.2	a
Mean	**8.0**	**3.4**	**AB**	**9.0**	**2.8**	**B**	**16.9**	**4.9**	**A**	**11.3**	
	Year 1994									Mean	
Cone	57.5	4.1	a	35.0	3.2	a	21.0	2.1	A	37.8	a
Control	25.3	11.3	b	13.6	3.6	b	1.4	0.4	B	13.4	b
Gravel	31.0	9.1	b	17.0	3.8	b	2.3	0.8	B	16.8	b
Pumice	30.9	9.1	b	11.4	2.5	b	2.0	0.8	B	14.8	b
Pyr. ind.	21.9	8.9	b	12.2	4.0	b	2.0	0.7	B	12.0	b
Mean	**33.3**	**8.5**	**A**	**17.8**	**3.4**	**B**	**5.7**	**1.0**	**C**	**18.9**	
	Total (1993+1994)									Mean	
Cone	70.0	1.3	a	46.5	2.5	a	34.4	0.9	A	50.3	a
Control	28.7	12.7	b	19.0	5.6	b	6.6	2.3	B	18.1	b
Gravel	33.6	10.2	b	19.6	4.2	b	11.2	1.8	b	21.5	b
Pumice	42.3	12.3	b	27.2	6.1	b	21.2	6.5	ab	30.2	b
Pyr. ind.	32.1	13.7	b	21.8	5.9	b	39.6	12.8	a	31.2	b
Mean	***41.3***	***10.0***	***A***	***26.8***	***4.9***	***B***	***22.6***	***4.9***	***B***	***30.2***	

Table 6. Statistical comparisons obtained from ANOVA on seedling emergence, number of seedlings surviving after first year, number of established seedlings after 4 years, and number of spots having one or more seedlings at the same time, using three species and seven regeneration methods in four blocks.

Variation	**Source**	**Df**	**MS**	**P**
Seedling emergence	Method	4	0.22538	0.000
	Species	2	0.24785	0.001
	Method*species	8	0.03813	0.006
Survival 1993-1994	Method	6	2.7041	0.000
	Species	2	0.0980	0.232
	Method*species	12	0.3013	0.000
Established seedlings after 4 years	Method	6	1514.822	0.000
	Species	2	850.682	0.000
	Method*species	12	417.285	0.000
Spots having 1> seedling after 4 years	Method	6	1142.560	0.000
	Species	2	5461.996	0.000
	Method*species	12	870.349	0.000

two summers were combined, the plastic cone method gave significantly higher seedling emergence than the other sowing methods (Table 5).

An interaction was found between species and methods when the results from 1993 and 1994 were examined together (Table 6), i.e. germination differed between methods among the species. Sitka spruce and lodgepole pine yielded the highest seedling emergence after two summers when sown under cones (Table 5), while Siberian larch was highest after the first summer when sown in pyramidal indentations. There was virtually no seedling emergence of Siberian larch in the second summer except under the cones. The total seedling emergence of Siberian larch after two summers was found to be highest when sown in pyramidal indentations (39.6%), closely followed by plastic cones (34.4%). These methods gave significantly higher seedling emergence than the other methods used (Table 5).

Seedling survival and establishment

Seedling mortality was high during the first winter, except under cones, where more than 80% of the seedlings survived (Table 7).

In the beginning of the fourth growing season, the highest average seedling establishment ratio was achieved using cones (Figure 1). The cones gave similar results to autumn planting, but spring planting yielded the significantly highest seedling establishment.

Comparing species, lodgepole pine had the significantly highest number of established seedlings. When the three tree species were tested separately, the plastic cone method gave a significantly higher number of established seedlings than the other sowing methods. For Sitka spruce and lodgepole pine, direct seeding under cones gave similar results to the best planting method, but for Siberian larch, autumn planting gave a significantly higher number of established seedlings (Fig. 1).

Number of seed spots with living seedlings

The differences between species in the number of seeding and planting spots with one or more living seedlings were significant (P<0.05) at the beginning of the fourth growing season (Figure 2). Lodgepole pine gave significantly better results for all sowing methods than were achieved for Siberian larch and Sitka spruce.

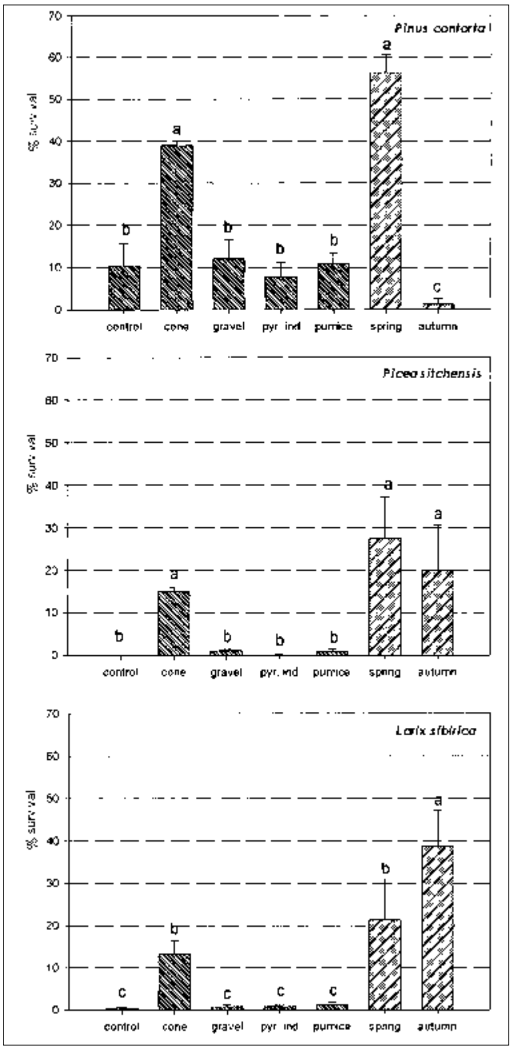

Figure 1. Data are presented as means and standard errors for the number of established seedlings at the beginning of the fourth growing season (1996), as percentage of sown, germinable seed. Values with different letters are significantly different (Tukey's HSD test, p<0.05). "Spring" and "autumn": survival of seedlings planted in spring and autumn of 1993.

Table 7. Seedling survival after the first winter expressed as percentage of living seedlings. Significant differences are indicated by different letters (Tukeys HSD, P<0.05).

	species											
	Pinus contorta	SE		Picea sitchensis	SE		Larix sibirica	SE		mean	
Control	28.2	13.5	b	2.1	1.2	c	3.8	2.2	C	11.4	c
Cone	81.3	18.8	a	85.7	12.0	a	100.0	0	A	89.0	a
Gravel	10.7	4.1	b	14.2	6.4	c	5.0	2.8	C	10.0	c
Pumice	27.7	11.1	b	14.2	4.5	c	1.8	0.8	C	14.6	c
Pyr ind	28.6	2.3	b	9.7	8.0	c	1.1	0.5	C	13.1	c
Spring	87.5	3.2	a	62.5	13.0	ab	56.3	19.1	B	68.8	b
Autumn	5.0	3.5	b	36.3	13.0	bc	87.5	6.3	ab	42.9	b
Mean	**38.4**	**8.1**	**A**	**32.1**	**8.3**	**A**	**36.5**	**4.5**	**A**		

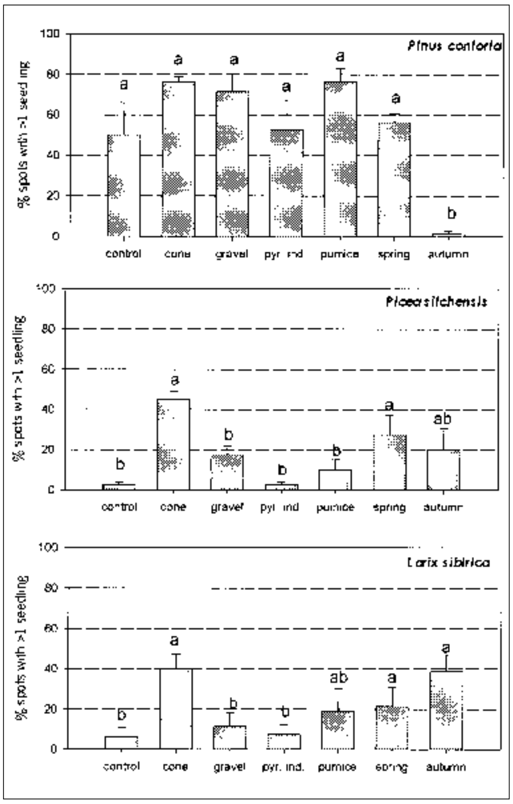

Figure 2. Data are presented as means and standard errors for the number of seeding- or planting spots having one or more living seedlings at the end of the fourth growing season in 1996. Values with different letters are significantly different (Tukey's HSD test, p<0.05). Spring and autumn refers to survival of seedlings planted in spring and autumn of 1993.

Significant differences were also found when different regeneration methods were compared among the species. Using plastic cones was found to be significantly (P<0.05) the most beneficial method, resulting in more than twice the number of seed and planting spots with one or more living seedlings for all species (53.9% for cones, vs. 19.6-35.0% for other methods).

There was a significant interaction between tree species and methods, i.e. different regeneration methods appear to favour different species (Table 7). Autumn planting gave by far the poorest results for lodgepole pine (1.3%) of all methods compared. The reason for the particularly poor outcome of autumn planting of lodgepole pine in this experiment was not determined; however, winter desiccation is a commonly observed causal agent in winter mortality of lodgepole pine on exposed sites in South Iceland (A Sigurgeirsson and JG Pétursson, personal observation). Other methods did not differ significantly, yielding 50.0 – 76.3% of seeding per planting spots occupied by a living seedling by the end of the fourth growing season.

For Sitka spruce, sowing under cones was a significantly better method than other direct seeding methods, but not significantly better than planting.

For Siberian larch, the cones gave the highest number of spots (40.0%) although this was not significantly different from sowing with pumice (18.8%) or spring (21.3%) or autumn (38.8%) planting.

DISCUSSION

Seedling emergence

Seedling emergence of boreal conifer seeds in the control in Mosfell ranged from 6.6% to 28.7% depending on species. This was considerably lower than reported by Winsa (1995), where a 55% seedling emergence was obtained for Scots pine in Sweden. Our results were, however, similar to those presented by Hagner (1976), also in Sweden, where 2-21% of the Scots pine seeds sown on scarified spots formed seedlings. For Norway spruce (*Picea abies* (L.) Karst.) and Scots pine, Hagner (1990) suggests that 20-30% of seeds sown on mineral soil form seedlings in the first summer. Thus, the total seedling emergence after direct seeding of conifer seeds in the current study was similar to what has been obtained in a country where the method is considered a viable alternative for forest regeneration.

The highest seedling emergence was obtained when sowing under plastic cones (see Figure 3). The cones improve temperature and moisture, two crucial environmental factors for seed germination and seedling emergence (Lähde & Tuohisaari 1976). On exposed terrain in a cold climate, such as in Iceland, this increment is of great importance and the temperature difference between the inside and outside of the cone is probably even higher due to shelter.

In contrast to what is commonly found with direct seeding, where most of the seeds germinate during the first summer, a large proportion of the seeds in Mosfell germinated during the second summer. This has also been observed in northern Sweden where approximately 25% of the lodgepole pine seeds sown under cones did not germinate until the second summer (Hagner 1984). The reason for the high germination during the second summer in southern Iceland was probably due to the cold climate. The seeds require a minimum temperature threshold for germination and at low temperatures germination is slow (Winsa 1995). The mean temperature in July in Mosfell is only about 11°C and the topsoil summer temperature on lowland sites in Iceland is commonly

Figure 3. Sowing under a 'Cercon' plastic cone gave the highest seedling emergence of the seeding methods tested in the experiment at Mosfell, yielding an average of 50.3% seedling emergence for all species. (a) A plastic cone at the start of the experiment (in spring of 1993). (b) An established lodgepole pine seedling four summers later (in 1997), grown from seed that germinated on site under a plastic cone. Note that the plastic cone degrades over a period of 2-3 years when exposed to sunlight. Photos: J.G.P.

10 to 12°C (Einarsson 1976). The delay in germination may be considered beneficial as it spreads the risk of unfavourable environmental conditions such as summer drought and harsh winters. This can also promote the spurning of uneven stands, which can improve the future quality of the wood, given that proper silvicultural methods are applied (Hagner 1992). Summer temperature, however, is the single most limiting factor affecting tree growth in Iceland (Sigurgeirsson 1988) and therefore there is a risk that the seedlings germinating

late in the growing season will not be adequately developed before autumn frosts.

It is important that the seeds get adequate and reliable moisture to be able to germinate and establish seedlings (e.g. Hegarty 1978, Oleskog 1999). During the first summer, the methods that were supposed to improve the moisture conditions most, i.e. the plastic cone, pyramidal indentations and pumice, gave the highest seedling emergence. During the second summer this effect vanished and the seedlings in control spots and gravel emerged as well as in pyramidal indentations and pumice.

Seedling survival and establishment

After the first winter there was much greater survival of the seedlings under the cones compared to other seeding methods. Under the cones the seedlings were protected from the desiccating winds. The lack of such protection was likely an important factor contributing to the mortality observed for the other methods. The cones can also inhibit frost heaving, which was the other main factor leading to mortality. Frost heaving is very common in Icelandic soils due to the soil structure and the frequent fluctuations of air temperatures around 0°C during the winter, and is a common cause of seedling mortality (Aradóttir & Magnússon 1992). The cones cannot, however, protect the seedlings from the vine-weevil larvae (*Otiorhyncus spp*.), which were recorded to have killed seedlings in all methods. The larvae live in the soil and eat the roots of the seedlings from below (Halldórsson 1994). Another factor explaining the higher survival of the seedlings under the cones is that they are usually larger and better developed due to the favourable environment (Lähde & Tuohisaari 1976, Hagner & Sahlén 1977). This is extremely important in the cool, maritime Icelandic climate during the growing season, which reduces growth of the seedlings (Winsa 1995).

The current study shows that using the plastic cones can significantly improve the rate of survival and seedling emergence obtained by direct seeding of conifer seed in Iceland, by ameliorating microclimatic conditions during the growing season or winter. It must be stressed however that the results are restricted to the drained andosols on the exposed lowlands of South Iceland. Forestry conditions are very variable between various locations in the country (Blöndal 2001).

Seed predation

Seed predators will strongly influence the success of direct seeding (Bergsten 1985). Iceland has few mammalian species and because of the lack of forests, there are relatively few seed-eating, forest-dwelling birds. However, in the summer of 1993 it was noticed that the trials had suffered from seed predation. During the first weeks following sowing, many of the larger, Siberian larch seeds disappeared or were eaten on site, as indicated by the seed shells left behind. This suggests that seed predation is a problem in Iceland, especially on seed of species with large seeds, such as Siberian larch. Although it was beyond the scope of the present study to determine which animal was involved, the European wood mouse (*Apodemus sylvaticus* L.) would appear a likely culprit. It is common throughout the lowlands of Iceland, and in other European countries tree seed is an important part of its diet. In fact, the species is considered an important agent for the transportation and burying of tree seeds (Nowak 1991).

Lodgepole pine

Lodgepole pine had the highest seedling emergence in 1993 and 1994 of the species tested, with almost double that of the other species. The plastic cones gave by far the highest number of emerged seedlings among the methods for lodgepole pine and gave the highest survival after the first winter, resulting in by far the largest number of established seedlings in the beginning of the fourth growing season. Hagner (1984) presents results from northern Sweden, where sowing lodgepole pine under plastic cones yielded 75% of the viable seeds as seedlings after two growing seasons. This can be compared to the results from Mosfell where seedlings emerged from 70% of the viable seeds under the plastic cones.

When compared to direct seeding, spring planting gave a similar number of filled spots in the beginning of fourth growing season. Autumn planting yielded very poor results for lodgepole pine, resulting in only 5% living seedlings. The reason could be due to susceptibility of lodgepole pine to desiccation during late winter and early spring, when sunny days occur, usually with severe winds, on frozen soil.

From these results it can be argued that the plastic cone is the best method used in the trial for direct sowing of lodgepole pine, when the aim is to secure afforestation success at a low cost. By the beginning of the fourth growing season it was fully comparable with the success rate obtained by spring planting.

Sitka spruce

The total seedling emergence of Sitka spruce at Mosfell was found to be significantly highest under cones, whilst the other seeding methods did not differ significantly from each other.

Late summer frost was observed to cause mortality of the spruce seedlings at Mosfell. Sitka spruce is very susceptible to late summer frosts (Skúlason *et al*. 2001), which frequently occur on lowland areas in Iceland. Therefore it might be concluded, as did von Ow *et al*. (1996), that it is necessary to provide some shade for natural regeneration of Sitka spruce to protect the seedlings from climatic extremes.

Another factor leading to increased mortality of Sitka spruce seedlings is nutrient deficiency, which may predispose seedlings to other lethal factors. Óskarsson *et al*. (1997) concluded that the soils at Mosfell are extremely deficient in available phosphorus and nitrogen. His results after two growing seasons indicated, furthermore, that survival can be improved by the use of the proper amounts of N-P fertilizers. It should be noted that the site of this study has the same soil characteristics as in the study of Óskarsson *et al*. (1997), and the spruce seedlings followed in this study have not to date received any N-P fertilizer.

It can be concluded that for Sitka spruce on exposed moss-heaths in South Iceland, regeneration results may be equally good when sown under plastic cones as in spring planting.

Siberian larch

Siberian larch had the highest total seedling emergence of the species used after the first summer but significantly lower than the other species during the second summer. The results after the first summer were mostly due to the high seedling emergence obtained when sown in pyramidal indentations, whereas the other methods gave similar results as for the other species. It seems that the pyramidal indentations in the soil, which enhance the moisture conditions (Bergsten 1988), promote seedling emergence from the larger Siberian larch seeds more than the other methods tested.

In the second summer, the seedling emergence was very low for all methods except under plastic cones. By then the surviving viable seeds had been eaten, perhaps by the wood mouse, and hence none were left to germinate. Under the cones, however, the seeds are protected from predators such as mice or birds. The seedling emergence under the cones had almost doubled after the second summer. This means that Siberian larch performs like lodgepole pine and Sitka spruce in southern Iceland, in that more seedlings emerge the second summer, provided of course that the seeds have not been devoured.

The seedling emergence of Siberian larch under cones has been investigated in Finland by Lähde & Tuohisaari (1976), who found it to be approximately 28% under factory-made cones. That is similar to the findings obtained from Mosfell, where the result was 34.4%.

The survival of the Siberian larch seedlings was significantly highest under the cones after the first winter and similar to the survival of seedlings planted in the autumn.

The number of spots with living seedlings in the beginning of the fourth growing season was lower for spring planting (21.3%) than autumn planting (38.8%) and seedlings under cones (40.0%) (Figure 1). A possible explanation for this high mortality is offered by Óskarsson and Ottóson (1990). Siberian larch is adapted to a continental climate and hence more susceptible to early spring frost in the mild, maritime winter climate of the southern Icelandic lowlands, and this lack of adaptation might be responsible for some of the seedling mortality. Furthermore, the deficiency of nitrogen and phosphorus may be a factor contributing to mortality of Siberian larch on this site, as demonstrated by Óskarsson *et al*. (1997).

The method of sowing under plastic cones was, therefore, the only regeneration method comparable to that of autumn planting at the beginning of the fourth growing season at Mosfell.

CONCLUSIONS

After of studying direct seeding results during four growing seasons in South Iceland, a few conclusions can be made:

- The germination and seedling emergence of lodgepole pine, Sitka spruce and Siberian larch seed in South Iceland is comparable to other countries at similar latitudes.
- Seedling emergence increased in the second summer.
- Direct seeding of lodgepole pine gave by far the best results of the species tested, both concerning germination and seedling establishment.
- Of the seeding methods tested the plastic cone was found to be the most beneficial for all the tree species. In the beginning of the fourth growing season the plastic cone was the only method that was comparable to planting in terms of regeneration success.
- The survival of planted seedlings was higher for Siberian larch when planted in the autumn, but higher for lodgepole pine and Sitka spruce when planted in spring.

From these findings, drawing upon four years of study, direct seeding of lodgepole pine using plastic cones as shelter can be recommended as an afforestation method on the freely drained andosols in South Iceland. Further research is needed to analyse the economical and practical use of this method. Further research should be carried out aimed at improving seedling establishment and vigor when applying direct seeding. Furthermore, differences between sites and locations should be analysed with respect to the general applicability of direct seeding as an afforestation method.

ACKNOWLEDGEMENTS

We wish to thank Vignir Sigurdsson for help during the fieldwork and Owe Martinsson, Ása L. Aradóttir, Thórarinn Benedikz and Thröstur Eysteinsson for their helpful suggestions on the text at various stages. Thórarinn Benedikz and Erla Gudjónsdóttir provided the seed used in this study and carried out germination tests in the seed laboratory at the Icelandic Forest Research, Mógilsá. The work was supported by the National Science Council of Iceland (RannÍs), the Foundation for Agricultural Production in Iceland, the Icelandic Forestry Association and the Iceland Forest Service. We are grateful for their support.

REFERENCES

Aradóttir ÁL & Magnússon S 1992. Ræktun landgræðsluskóga 1990 – Árangur gróðursetninga [Planting of restoration forests in 1990 - Seedling establishment]. *Ársrit Skógræktarfélags Íslands 1992,* 58-69. (In Icelandic, English summary).

Arnalds A 1987. Ecosystem disturbance in Iceland. *Arctic Alpine Res.*19, 508-513.

Bergan J & Eide T 1988. Beskyttesåing som foryngelsemethode på våre nordlige breddgrader [Protected seeding as regeneration method at northern altitudes in Norway]. *Norw. For. Research Institute, Rapport* 3/88, 1-20. (In Norwegian, English summary).

Bergman F & Bergsten U 1984. Improvement of germination by seeding through mechanical soil preparation. In: Perttu K (ed.)

Ecology and management of forest biomass production systems. Dept. Ecol. and Environ. Res., Swed. Univ. Agric. Sci. Rep. 15, 291-307.

Bergsten U 1985. A study on the influence of seed predators at direct seeding of *Pinus sylvestris* L. *Swedish Univ. Agric. Sciences, Dept. of Silviculture, report no. 13,* 15 p.

Bergsten U 1988. Pyramidal indentations as a microsite preparation for direct seeding of *Pinus sylvestris* L. *Scand. J. For. Res*. 3, 493-503.

Bishop T & Lentner M 1986. *Experimental designs and analysis*. Valley Book Company, Blacksburg, USA, 186 p.

Blöndal S, Benedikz Th & Ottóson JG 1986. Forestry in Iceland: A brief description of its history and present status. *Iceland Forestry Service, Forest report nr. 8,* 32 p.

Blöndal S 2001. Development of forestry in Iceland during the 20th century. *Skógræktarritið 2001,* 83-87.

Burdett AN, Coates H, Eremko R & Martin PAF 1986. Toppling in British Columbia's Lodgepole pine plantations; Significance, cause, and prevention. *Forest. Chron*. 62, 433-439.

Dominy SWJ & Wood JE 1986. Shelter spot seeding trials with jack pine, black spruce and white spruce in Northern Ontario. *Forest. Chron*. 62, 446-450.

Einarsson MA 1976. *Veðurfar á Íslandi* [Climate in Iceland]. Iðunn, Reykjavik. 150 p. (in Icelandic).

Graber R 1988. Stem quality of white pine established by seeding in furrows and by planting. *North. J. Appl. For.* 5, 128-129.

Hagner M 1976. Punktsådd med täckning av sand eller cellulosafiber [Spot seeding with the seed coverd with gravel or cellulose fibers]. *Sveriges Skogsvårdsförb.s Tidsskr*. 76, 657-668. (In Swedish, English summary).

Hagner M 1984. Överlevnad och tillväxt under nio år hos konsådd tall (*Pinus silvestris* och *Pinus contorta* [Survival and growth of pine (*Pinus sylvestris* and *Pinus contorta*) during nine years following direct seeding under plastic shelters]. *Sveriges Skogsvårdsförb. Tidsskr*. 84, 5-21. (In Swedish, English summary).

Hagner M 1990. Direct seeding of pine and spruce in Sweden. In: Titus BD, Lavigne MB. Newton PF & Meades WJ (eds.) *The silvics and ecology of boreal spruces*. 1989 IUFRO working party S1.05-12 Symp. Proc. Newfoundl., 12-17 Aug. 1989. For. Can. Inf. Rep. N-X-217, pp. 55-62.

Hagner M 1992. Naturkultur: befriande gallring kombinerad med berikande plantering [Natural silviculture: release thinning combined with supplemental planting]. *Skog och forsking, 4, 10-16.* (In Swedish)

Hagner M & Sahlén K 1977. Sådd i plastkon på markberedd mark [Direct seeding under plastic cones on scarified ground]. *Sveriges Skogsvårdsförb. Tidsskr*. 77, 59-86. (in Swedish, English summary).

Halldórsson G 1994. Ranabjöllur [*Otiorhyncus*: a serious problem in forestry in Iceland]. *Skógræktarritið* 1994, 53-58. (In Icelandic, English summary.)

Hegarty TW 1978. The physiology of seed hydration and dehydration, and the relation between water stress and the control of germination: a review. *Plant, Cell, Environment* 1, 101-119.

Lähde E & Tuohisaari O 1976. An ecological study on effects of shelter on germination and germling development of Scots pine, Norway spruce and Siberian larch. *Metsantutkimuslaitoksen Julkaisuja* 88, 1-37.

Nowak RM 1991. *Walker's Mammals of the World.* 5th Ed. Vol II. Johns Hopkins University Press, Baltimore. 1629 p.

Nilson H. & Hjältén J 2003. Covering pine seeds immediately after seeding: effects on seedling emergence and on mortality through seed-predation *For. Ecol. Manag.* 176, 449-457.

Oleskog G 1999. *The effect of seedbed substrate on moisture conditions, germination and seedling survival of Scots pine*.

Doctoral dissertation, Swedish Univ. Agric. Sciences, Dept. of Forest Management and Products, Uppsala. 25 p.

Óskarsson Ú & Ottóson JG 1990. Plantation establishment success of *Pinus contorta* Dougl. ex Loud and *Larix sibirica* (Munchh.) Ledeb. using various methods and stock. *Scand. J. For. Res*. 5, 205-214.

Óskarsson H, Sigurgeirsson A & Helgason B 1997. Áburðargjöf á nýgróðursetningar í rýrum jarðvegi á Suðurlandi [Fertilization of seedlings at planting on nutrient-deficient soils in South Iceland]. *Skógræktarritið* 1997, 42-59. (In Icelandic).

Ow F von, Joyce P & Keane M 1996. Factors affecting the establishment of natural regeneration of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. *Irish Forestry* 53, 2-18.

Pétursson JG 1995. *Direct seeding of Sitka spruce, lodgepole pine and Siberian larch on scarified seed spots in southern Iceland, using various methods*. Report no 40, Swedish Univ. Agric. Sciences, Department of Silviculture, 45 p.

Pétursson JG 1999. Skógræktaröldin. Samanteknar tölur úr Ársriti Skógræktarfélags Íslands [The first 100 years of tree planting in Iceland]. *Skógræktarritið 1999(2)*, 49-53. (In Icelandic, English summary).

Pétursson JG & Sigurgeirsson A 1997. Beinar sáningar á barrtrjáfræi [Direct sowing of coniferous seed]. Skógræktarritið 1997, 75-87. (In Icelandic, English summary).

Putman WE & Zasada JC 1986. Direct seeding techniques to regenerate white spruce in interior Alaska. *Can. J. For. Res*. 16, 660-664.

Rosvall O 1994. Contortatallens stabilitet och motståndskraft mot vind och snö [Stability in Lodgepole pine and resistance to wind and snow loads]. *SkogForsk*, *Redogörelse* nr 2, 44 p. (In Swedish, English summary).

Sahlén K 1984. Uppföljning av det biologiska resultatet efter konsådd vid praktisk tillämpning [Investigation of the reforestation result after direct seeding under plastic cones]. *Sveriges Skogsvårdsförb. Tidsskr*. 5, 21-45. (In Swedish, English summary).

Saksa T & Lähde E 1982. Siemenen määrä männyn kuusen ja lehtikuusen suojakylvössä [Number of seeds in shelter sowing of Scots pine, Norway spruce and Siberian larch]. *Folia For*. 541, 1-16. (In Finnish, English summary).

Sigurdsson BD & Snorrason A 2001. Carbon sequestration by afforestation and revegetation as a means of limiting net-CO_2 emissions in Iceland. *Biotechnology, Agronomy, Society and Environment* 4, 303-307.

Sigurgeirsson A 1988. Stafafura á Íslandi. Vöxtur, ástand og möguleikar [*Pinus contorta* Dougl. in Iceland: growth, condition and potential]. *Ársrit Skógræktarfélags Íslands* 1988, 3-36. (In Icelandic, English summary).

Skúlason B, Sigurgeirsson A, Guðleifsson BE & Edvardsen ØM 2001. Frost tolerance among provenances and families from the Picea complex in Alaska. *Skógræktarritið* 2001, 188-190.

Wennström U, Bergsten U & Nilson JE 1999. Mechanized microsite preparation and direct seeding of *Pinus sylvestris* in boreal forests - a way to create desired spacing at low cost. *New Forests* 18, 179-198.

Winsa H 1995. *Effects of seed properties and environment on seedling emergence and early establishment of Pinus silvestris* L. *after direct seeding*. Doctoral dissertation, Swedish Univ. Agric. Sciences, Dept. of Silviculture, Umea, 22 p.

Zar JH 1984. *Biostatistical analyses*. Prentice-Hall, Inc. Englewood Cliffs, New Jersey, USA, 18 p.

Manuscript received June 8, 2004
Accepted November 4, 2004