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Supplementary information for Guidelines for the use of the Decision Support System "Calculating Wilding Spread Risk From New Plantings"

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Report information sheet

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Supplementary Tables

S1. Years to maturity

Species	Common	Years to maturity (coning)
Pinus contorta	lodgepole	5-10 (Burns and Honkala 1990) 5-13 (Allsop 1951) (3-4) 7-8 (Benecke 1967) (3) 5-13 (Weston 1957) (4) 5-6 (Critchfield 1980) >5 (Ledgard 2001) 5 (Ledgard 1988) 5-13 (Hunter and Douglas 1984) 3-8 (Paul et al.2023) 4, 5, 5, 5, 8, 14 (6.8) (Franzese and Raffaele 2017) "Lodgepole pine begins bearing cones with vi-able seeds at a very young age — in open stands by trees 5 to 10 years old, in more densely stocked stands by age 15 to 20 years — and continues well past maturity (Crossley 1956b Tackle 1961a). Seed from trees less than 10 years old can have as high a germination percentage as seed from mature trees. (Alexander 1974) "The earliest year of cone production recorded among the trees sampled in this study was 1997, when trees that germinated in 1989 would have been 8 years old, and all stands were producing cones by 2002, when trees were up to 13 years old. However, the variation in onset of cone production was not related to either tree size or stand density. Results from one-way ANOVA revealed a marginally significant influence of elevation class, with the onset of cone production occurring sooner in stands <2300 m in elevation (r 2 = 0.23, M.S.E. = 7.56, F = 4.26, P = 0.06)." (Turner et al.2007) "Lodgepole pine first produces cones at varying ages, from 5 to 20 years. At Sulphur Springs, where it is much drier than in Estes Park, two 5-year seedlings were found each bearing two full-grown cones. In Mills Park the youngest cone-bearing pine found was 12 years old, and as a rule the first cones appeared in the fifteenth year." (Clements 1910)"
Pinus sylvestris	Scots	"begin… at 5 to 8 years, although the average is between 10 and 15 years" (Burns and Honkala 1990) 12-15 (Weston 1957) 10 (Ledgard 1988) 25-30 (Calama et al.2017)

Species	Common	Years to maturity (coning)
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	(austriaca) 25-30 (Weston 1957) (laricio) 13-21 (Weston 1957) 18 (Ledgard 1988) 13-21 (Hunter and Douglas 1984) 15-40 (Calama et al.2017) "Minimum seed-bearing age is 15 to 40 years. In England, black pine from Corsican sources produce their first heavy cone crops at ages 25 to 30 years and reach maximum production between 60 and 90 years of age" (Burns and Honkala 1990)
Pinus ponderosa	Ponderosa	18–24 (Allsop 1951) 25–30 (Weston 1957) 20 (Ledgard 1988) 18-24 (Hunter and Douglas 1984) "as early as 7 years" (Burns and Honkala 1990) "15, 15.4, 17, 18, (16.3)" (Franzese and Raffaele 2017)
Pinus muricata	bishop	8–10 (Allsop 1951) 8–10 (Weston 1957) 10 (Ledgard 1988)
Pinus pinaster	maritime	18–24 (Allsop 1951) 8 (Ledgard 1988) 10-12 (Hunter and Douglas 1984) "6,10, (8)" (Franzese and Raffaele 2017) 10-15 (Calama et al.2017)

Species	Common	Years to maturity (coning)
Pinus radiata	Monterey	8 (Weston 1957) 9-12 (Hunter and Douglas 1984) 10 (Ledgard 1988) "6, 6, 8, 9, (7.2)" (Franzese and Raffaele 2017) "Fertile cones are produced as early as 5 to 10 years, but substantial crops are not yielded until age 15 or 20 if the trees are open-grown, and considerably later if the stands are dense." (Burns and Honkala 1990)
Pinus x attenuata	knobcone	8 (Weston 1957)
Pseudotsuga menziesii	Douglas fir	18–20 (Allsop 1951) 15–20 (Weston 1957) 12 (Ledgard 1988) 12-15 (Burns and Honkala 1990) 18-20 (Hunter and Douglas 1984) "7, 10.9, 11, 18, (17)" Franzese and Raffaele 2017 "*Pseudotsuga menziesii* became reproductively mature at 10.9 ± 1.26 years (±SE)." (Orellana and Raffaele 2010)
Larix decidua	European larch	11–18 (Allsop 1951) 10 (Weston 1957) 12 (Ledgard 1988) 11-18 (Hunter and Douglas 1984)
Larix laricina	tamarack	12-15 years (or less) (Burns and Honkala 1990) "In eastern Ontario viable seed has been collected from vigorous plantations as young as 4 years" (Burns and Honkala 1990)

Species	Common	Years to maturity (coning)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	"Redwoods start to bear seeds when 5 to 15 years old" (Burns and Honkala 1990)
Sequoiadendron giganteum	Giant redwood	"Cones bearing fertile seeds have been observed on trees as young as 10 years of age, but the large cone crops associated with reproductive maturity usually do not appear before about 150 or 200 years." (Burns and Honkala 1990)
Picea abies	Norway spruce	>35 (Weston 1957)
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	"Sitka spruce may occasionally produce cones before 20 years of age, but cone bearing in stands usually does not begin until ages 20 to 40" Burns and Honkala 1990) variable (Weston 1957)
Abies grandis	grand fir	"Seed production begins at about 20 years of age and increases with age, diameter, and vigor of the tree." (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	8–9 (Allsop 1951) 8–9 (Weston 1957) "Seed production starts when the tree is 5 to 20 years old" (Burns and Honkala 1990)
Thuja plicata	western red cedar	11-14 (Allsop 1951) "When grown in the open, western redcedars begin to produce strobili at 10 years of age and usually every other year thereafter." (Burns and Honkala 1990)

Species	Common	Years to maturity (coning)
Cryptomeria japonica	Sugi, Japanese cedar	9–14 (Allsop 1951) 9–14 (Weston 1957)
Cedrus deodara	Deodar cedar	

S2. Cone production

Species	Common	Cone production/ cones per tree
Pinus contorta	lodgepole	1480.4 ± 1888.3 (n = 27–30) 1998 (Wall 2008) 1693.2 ± 2362.6 (n = 27–30) 1999 (Wall 2008) 202.1 ± 367.2 (n = 27–30) 2000 (Wall 2008) 7309.9 ± 8120.6 (n = 27–30) 2001 (Wall 2008) 1389.6 ± 1337.6 (n = 27–30) 2002 (Wall 2008) Average = 2415 ± 2797 (Wall 2008) "Clements (1910) cone counts varied from none in suppressed trees to 9,000 for open-grown trees" (Lotan 1975) Means by Province: 6, 32, 39, 32, 20, 24,37, 27 (O'Reilly and Owens 1988) "In New Zealand cone numbers vary greatly between trees and years. Numbers of 1-year-old cones on a sample of 17, 10-year-old trees planted in uniform sheltered nursery conditions varied from 22±335 with a mean of 128" (Ledgard 2001) "Mean cone abundance was 3.7 cones tree-1 but ranged from 0.1 to 17.8 cones tree-1 among the 16 stands. Multiple regression revealed that 77% of the variation in cones per tree among stands was explained by mean basal diameter and elevation (Table 1). More cones per tree were observed in stands with larger trees and at lower elevations (Fig. 2)" (Turner et al.2007) "When tree density was multiplied by the mean cones per tree in each stand, we found an expected cone density ranging from 1082 to 1,015,665 cones ha-1. Stand density was the strongest predictor of cone density (Fig. 3), but an additional (albeit marginally significant) negative influence of elevation was also identified (Table 1). (Turner et al.2007) "Considering only trees on which cones were present (n = 165), we observed an average of 9.5 cones tree-1 (S.E. = 1.0) and a maximum of 73 cones tree-1. Trees with cones had an average basal diameter of 5.7 cm (S.E. = 0.19 cm), but cones were present on trees ranging from 1.4 to 11.1 cm basal diameter. However, more cones were present on larger trees (Fig. 4). Variability in cone abundance among individual trees was explained by basal diameter (b = 3.08, r 2 = 0.45, P = 0.005). Cone production also varied among years (P < 0.0001, F = 75.37, d.f. = 6) with the greatest annual mean cones per tree produced during 2002 (Fig. 5). (Turner et al.2007) The number of cones borne by a single adult tree ranges from none in suppressed individuals to a maximum of 9,000 in a 99-year tree in an open stand. The density of the stand is of the first importance in cone production, and with variations due to age serves to explain the most striking differences. Trees which stand alone or in open groups tend to produce the maximum of cones, owing to their large crowns. Upon mature trees in dense stands the total number of cones rarely exceeds a few hundred. In more open situations the minimum usually exceeds 2,000, and for trees from 80 to 99 years actual counts gave a range of from 2.020 to 9000 cones.

Species	Common	Cone production/ cones per tree
		Trees 40 to 50 years old, in the open, gave a range of from 257 to 1,520 cones, and in dense stands from 0 to 64." (Clements 1910) "The number of cones has no fixed relation to the amount of seed produced. The number of seeds in a cone depends upon its size, the age of tree or branch, the number of scales, and whether each scale bears 1 or 2 seeds or none at all. The basal scales of a cone do not bear seeds, and from 3 to 6 scales at the tip are also without them. The remainder of the cone between the tip and base has few scales that are seedless. The ratio of scales to seeds varies as much between different cones on the same tree as between those on different trees. The following table, based on 25 cones from the Targhee National Forest, shows the relation between scales and seeds:" (Clements 1910)
Pinus sylvestris	Scots	"The average total density of cones (shed plus those fed on and dropped by seed-eaters) produced by different cohorts is shown in Figure 5. Peaks in cone production (mast years) were in 1994, 1997 and 2000, coinciding with peaks in seed fall (Figure 2). Thus, there were significant correlations between seed fall and cone production for the four sites: Ice Wood, $r = 0.989$, $P < 0.001$); Bognacruie, $r = 0.943$, $P < 0.001$; Memorial Wood, $r = 0.938$, $P < 0.001$; Tore Hill, $r = 0.938$, $P < 0.001$. In addition, there was synchrony among sites in the cone production. In the six pair-wise comparisons among the four sites, Pearson correlation coefficients ranged from 0.759 ($P = 0.007$) to 0.963 ($P < 0.001$). There were significant differences among cohorts ($\chi 2 = 318$, d.f. = 10, $P < 0.001$), but not amongst sites ($\chi 2 = 2.9$, d.f. = 3, n.s.)." (Summers and Proctor 2005) "The peaks in cone production ranged from 27.1 to 39.2 cones m−2 of ground under the crowns whilst the lows ranged from 2.0 to 5.7 cones m-2 (Table 2)." (Summers and Protor 2005) "Seed trees that had been released for more than 6 years in 1995 had 333 cones per tree compared with 61 and 128 cones for unreleased trees and trees that had been released for less than 3 years, respectively (Fig. 2). The differences among groups were significant ($F2,5 = 4.0$, $P = 0.093$). In 1996, the lowest mean number of cones per seed tree (386) was found in trees released 1 or 2 years previously. The highest mean number (2355) was found in trees released 4 or 5 years previously (Fig. 2). ANOVA revealed significant differences associated with the length of time since release ($F4,10 = 55.3$, $P < 0.001$)." (Karlsson 2000) “Tree competitive status had a strong effect on cone production in both years (Kruskal-Wallis test, $P < 0.001$, Fig. 1). In 1998, isolated trees produced a mean of 994 cones (s.e. 177), though dominant and suppressed trees produced means of 234 (s.e. 54) and 70 (s.e. 31) cones, respectively. In 1999, cone production was much lower than in 1998 and the correlation between the production in the two years was significant and positive ($r2 = 0.64$, $P < 0.001$). Isolation also had a strong effect on cone distribution in the canopy (Fig. 2): isolated trees had only 57% of their cones in the highest half of the tree whereas within-stand trees had 94% of their cones in this part of the tree (ANOVA with arcsine transformation for proportional data, $P < 0.0001$). More than 80% of the cones from isolated trees were located in the middle part of the tree. This effect of competitive status was not simply related to tree dimensions. Fig. 3 shows linear regressions between tree characteristics and cone production in 1998. For any given size, an isolated tree produced many more cones than a within-

Species	Common	Cone production/ cones per tree
		stand tree. The best predictor of cone production for isolated trees was tree height (adj. r2 = 69.9%). However, in this tree type age, stem basal area and tree height were strongly correlated and all of these variables are significantly related to cone production. For dominant trees, the age of the tree was the only variable significantly related to cone production (adj. r2 = 55.2%). Cone production of suppressed trees was not correlated with any measured tree dimension." (Debain et al.2003) "The number of cones per reproductive tree (ignoring for now the 6 trees which had no cones) during the 3 years ranged between 31 and 2,418, with a total average of 685 cones tree-1 y-1 (Table 2), with a mean of 1,293 cones per tree in the most successful season and 92 cones per tree in the most unproductive season (Fig. 3a). Most cones sampled in the first 2 years, the most productive seasons, had between 12 and 35 seeds per cone (Fig. 3b) and a length of 4.0–4.5 cm but there were a significant number of cones that produced more than 50 seeds each (Fig. 4). The mean number of seeds per cone per tree ranged from 9.4 ± 0.56 to 56.3 ± 0.42 (Table 2). We estimated the total number of seeds produced per tree using the average number of seeds produced per cone per tree and the total number of cones per tree (Table 2); this ranged from 403 to 93,233 seeds per tree." (Mukassabi et al.2012)
Pinus mugo complex	mountain	"Number of cones per shrub was significantly affected by plot, year and by their interaction (Fig. 7a). With the exception of year 1985, there was relatively low synchronisation of cone number per shrub among plots. The highest number of cones per shrub was recorded in P4 plot in 1994." (Vacek et al.2013)
Pinus nigra	black, Austrian	"Mean cones per tree (and the mean of the negative binomial distributions, μ) was greatest in 2009 at Mt Barker with 278.6 cones per tree, and was just 26 cones per tree in 1997 at Lake Ruataniwha." (Coutts et al.2012)
Pinus ponderosa	Ponderosa	188.4 ± 318.9 (n = 27–30) 1998 (Wall 2008) 90.8 ± 87.6 (n = 27–30) 1999 (Wall 2008) 0.0 ± 0.0 (n = 27–30) 2000 (Wall 2008) 72.1 ± 78.5 (n = 27–30) 2001 (Wall 2008) 122.1 ± 183.0 (n = 27–30) 2002 (Wall 2008) Average = 94.7 ± 69.0 (Wall 2008) "Seed cone production in Pinus ponderosa is variable, with 3 broad categories of contributing factors: differences between (1) years, (2) sites, and (3) individual trees (Table 1). Many years result in no cone production at all, and other years result in heavy production, with many cones on more than half the population (McDonald 1992). " (Krannitz and Duralia 2004) "TABLE 1. Variability in seed or cone production for *Pinus ponderosa* (PP). K = 1000. Location; Variation in seed or cone production; Time period; comments; Source California: 0–18K seeds · ha−1 to 400K 1200K seeds · ha−1 (yearly); 24 years 1958–1981; r2 = 0.76, P < 0.01 filled seeds and cone crop, 613 trees · ha−1; McDonald 1992

Species	Common	Cone production/ cones per tree
		Washington: 0–384 cones · tree−1, 48% variation attributed to year (P < 0.0001) and 9% to tree (P > 0.2) a; 7 years 1951–1957 followed; 8 different PP trees; Daubenmire 1960 Idaho and eastern Washington: 0–9.4K cones · 100 PP trees−1 32% variation attributed to site (P = 0.07), 28% to year (P = 0.002) a; 3 years 1967–1969; 12 widely dispersed sites, 42–770 PP · ha−1; Dale and Schenk 1978 Colorado: 4–12.3K cones · 100 PP trees−1 1.3% variation attributed to site (P > 0.2), 42% to year (P = 0.10) a, 4 years 1984–1987; 4 sites; Linhart 1987 Arizona: 1.2–29.7 cones · 100 PP trees−1 10 years 1956–1965; 62.5 PP · ha−1; Larson and Shubert 1970 Colorado: 0–7.7K cones · 100 PP trees−1; 10 years 1926–1935; 78 PP · ha−1; Roeser 1941 California: 0–338 cones · 100 PP trees−1; 21 years 1933–1953; 5 PP · ha−1, 9 *P. lambertiana* · ha−1, 48 *Abies concolor* · ha−1; P. Fowells and Shubert 1956" (Krannitz and Duralia 2004)
Pinus muricata	bishop	< 200, 36 years post fire (Bisbing et al.2023) "At the individual tree scale, cone abundance was related to tree size and tree density (Table 2; P < 0.001; marginal R2 = 0.27). Cone counts increased with tree size, and large trees generally had more than ten times as many cones as smaller trees (average of 76 cones per large tree compared to 31 cones for small trees, 17 cones for saplings, and 1 cone for seedlings; Fig. 4c). Cone production was negatively related to plot-level tree density (Table 2; β [odds ratio] = 0.66; P < 0.001) after accounting for the effects of tree size. The nested random effect of sampling plots and fire year explained much additional variation in cone production, and the conditional R2 was 0.99." (Bisbing et al.2023) "Increasing cone production with tree size corresponded to an increase in plot-mean cone production with time since fire (Fig. 4d), because large trees that tended to have more cones represented a greater proportion of the stand in older fires (Fig. S2)." (Bisbing et al.2023)
Pinus pinaster	maritime	"The average number of cones/adult of Stand 1 (58.2 cones/adult) was twice as large as for Stand 2 (33.9 cones/adult). In addition, a remarkable among-tree variation was found for both stands in the number of cones/adult, which varied between 1 and 587 in Stand 1, and between 1 and 193 in Stand 2. Both distributions were skewed with 25% of trees bearing less than 5 and 3.8 cones/adult for Stand 1 and 2, respectively." (Charco et al.2017) "Four variables affected intensity of fruiting in our model: winter weather of the flowering year, tree size, stand density and competition. Wet winters (indicated by lower NAOwinter) during the flowering year (2) lead to higher cone yields. These results suggest that the necessary conditions for high cone counts include a relatively dry winter followed by a relatively wet winter. Dry winters ensure the occurrence of cones by favoring development of cone primordia, and a subsequent wet winter ensures a high cone count by enhancing primordia survival, flowering and pollination success (Fig. 1a). Trees with larger diameter are predicted to

Species	Common	Cone production/ cones per tree
		produce a larger number of cones than smaller trees (Fig. 1b). This result has been previously documented in other species such as *Pinus ponderosa* (Krannitz and Duralia, 2004) and *Pseudotsuga menziesii* (Kassaby and Barclay, 1992), and is probably explained in part by the generally greater vigor of larger trees in even-aged stands. Higher tree vigor has also been shown to produce a higher number of recruits in next generation (González-Martínez et al., 2006). As thinning promotes diameter growth, an increase in cone production is expected as a longer-term benefit of thinning (Krannitz and Duralia, 2004). As stand density declines the number of cones produced by a given tree increases (Fig. 1c). This result is consistent with previous observations of increased cone production after thinning (Verkaik and Espelta, 2006; Ruano et al., 2013), and can probably be explained in part by the greater resources available for each tree in less dense stands, allowing more carbon to be allocated to reproductive efforts" (Bravo et al.2017)
Pinus radiata	Monterey	
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	
Larix decidua	European larch	
Larix laricina	tamarack	
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	
Sequoiadendron giganteum	Giant redwood	"Because of extended cone retention, a mature tree may have 10,000 to 30,000 cones at any given time, two-thirds" (Burns and Honkala 1990)
Picea abies	Norway spruce	

Species	Common	Cone production/ cones per tree
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	"In the Inland Empire, a good cone crop for grand fir is considered to be more than 40 cones per tree. A fair crop is 21 to 40 cones per tree" (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	
Thuja plicata	western red cedar	
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S3. Seed production

Species	Common	Seed production
Pinus contorta	lodgepole	173,000 to 790,000 seed/ha/yr production (Burns and Honkala 1990) 35,000 to 1.2 million seed/ha/yr seedfall non-serotinous (Burns and Honkala 1990) 99,000 to 222,000 seedfall serotinous (Burns and Honkala 1990) 59,409 ± 68,806 filled seeds/tree/yr (Wall 2008) "Smithers (1961) estimated the seed supply to be between 100,000 and 300,000 seed per acre in both types of cones." (Lotan 1975) "Bates (1930) estimated annual production of some 70,000 to 320,000 seed per acre, with half to a third of them available for annual seed fall" (Lotan 1975) Mean (n) / Maximum filled seeds per tree "Lodgepole pine (1250 mm annual Rainfall) (*Pinus contorta*) 10 yr 395 (52) /1566; Lodgepole pine (700 mm annual Rainfall) (P. contorta) 10yr 6630 (17) 17353" (Ledgard 2001) average 395/ tree (Ledgard 1996) average 6630/ tree (Ledgard 1996) Seed production: yes, a 12-year-old, 5 tree is capable of producing just under 15,000 viable seeds/year dispersal: wind viability: 79-90%, rarely drops below 70% germination: spring, germination low; 15°C seed bank: delayed germination still occurring after 4 years; will survive 10-20 years in dry storage at 4°C and maintain 79-90% germination (Timmins and Mackenzie 1995) "In one study over a 10-year period in central Colorado and southern Wyoming, the average amount of seed stored in closed cones was 2.5 to 3.5 times greater than the current crop (Bates 1930). The average number of sound seeds stored in closed cones ranged from 181,000 to 1,104,000 per acre." (Alexander 1974) "Lotan (1967a, 1968) studied the variation in serotinous cone habit and estimated the number of sound seeds stored in closed cones on four areas in Montana and Idaho (table 3). Most trees produced almost entirely either open or closed cones. Only 10 to 20 percent of the trees were classified as intermediate. The estimated number of sound seeds stored in closed cones varied from 0.8 to 3.2 million per acre." (Alexander 1974) "Seed production by individual trees and by stands also varies considerably. Seeds from old and new cones together averaged 50,000 per tree in Idaho and 21,000 per tree in Colorado (Clements 1910). Annual variations in seed production on felled trees during a 10-year period (1912-21) ranged from 0 to 135,000 per acre in southern Wyoming, and from 55,000 to 827,000 per acre in central Colorado (Bates 1930). In central Oregon, where the cones are non-serotinous and the total crop is released each year, annual production in uncut stands varied from 178,000 to 572,000 sound seeds per acre during a 3-year period (Dahms 1963). In the other year of the study, only 14,000 seeds per acre were produced. In Montana, annual seedfall in stands with predominately serotinous cones averaged 70,000 sound seeds per acre over a 4-year period (Boe 1956).

Species	Common	Seed production
		Tackle (1964) observed this Montana area for 2 more years and another area nearby for 2 years, and reported average annual release of 65,000 to about 90,000 sound seeds per acre. In similar stands in Alberta, average annual seedfall varied from 10,000 to 30,000 seeds per acre during a 3-year period (Crossley 1955). Most of the seed released in the predominately serotinous stands probably came from non-serotinous cones, and represents only a small proportion of the annual seed production in these stands." (Alexander 1974)
Pinus sylvestris	Scots	Mean (n) / Maximum filled seeds per tree "15yrs 3415 (10) /12341" (Ledgard 2001) Average 3415 / tree (Ledgard 1996) "*P. sylvestris* in the Central Range of Spain starts producing a high amount of cone and seeds at 25-30 years old (in isolated trees) or 40 years old (when growing in canopy) holding this capacity up to very high ages (Ruiz de la Torre and Ceballos, 1979; Rojo and Montero, 1996)." (Calama et al.2017) "Annual seed density mean values ranged from 150-300 seeds/m^2 (Calama et al., 2015b)" (Calama et al.2017) "The number of seeds released per hectare per day peaking at more than 40 000 in mid-May during rich seed years" (Hannerz et al.2002) total seed fall ha^{-1} x1000: Garpensberg 1993: 900; 1994:500; 1995:1500; 1996:1100. Knivsta 1996:1600(±49); 1997:200(±25); 1999:1100 (±82) (Hannerz et al.2002) "The total annual seed fall varied between 200 000 and 1.6 million seeds per hectare (Table 2), with standard errors at the Knivsta site from 25 000 to 82 000, or 3–12.5% of the mean. Standard errors could not be calculated for the Garpenberg site." (Hannerz et al.2002) "The results suggest that, generally, seed dispersal commences shortly after the temperature rises above 5 °C and heat sum starts to accumulate." (Hannerz et al.2002) "The periods by which 50% of the seed had fallen corresponded to heat sums of 50 to 100 degree-days at both sites and at all years"(Hannerz et al.2002) "In most years, the peak in seed fall took place in May and high seed fall often extended into June. In 1994 and 1998, the peak was in either May or June" (Summers and Proctor 2005) figure 2: annual seed production approaches 500 seed m-2 (or 5M ha-1) (Summers and Proctor 2005) "The mean number of cones per seed tree candidate in the unreleased forest stands was 61 in 1995 and 503 in 1996, while the mean 1000-seed weight was significantly higher in 1995 (4.4 g) than in 1996 (3.5 g)." (Karlsson 2000) "Linear regression showed that tree trunk diameter explained 43.1% of seed produced per tree ($r^2 = 0.431$; $P < 0.001$) (Fig. 6). Moreover, by applying the equation obtained by linear regression to the 24 trees examined that had cones, the number of seed produced by all trees estimated from total cone numbers and mean seeds per cone was 483,922, and the calculated number from the regression of seed production against trunk diameter was 479,846, a difference of just 4,076 seed (0.85%). After dividing trees into either young or old trees (with 50

Species	Common	Seed production
		years the divider) a linear regression showed no significant relationship between tree age and number of seeds produced by a tree." (Mukassabi et al.2012) 173,000 to 790,000 seed/ha/yr production (Burns and Honkala 1990) 35,000 to 1.2 million seed/ha/yr seedfall non-serotinous (Burns and Honkala 1990) 99,000 to 222,000 seedfall serotinous (Burns and Honkala 1990) 59,409 ± 68,806 filled seeds/tree/yr (Wall 2008) "Smithers (1961) estimated the seed supply to be between 100,000 and 300,000 seed per acre in both types of cones." (Lotan 1975) "Bates (1930) estimated annual production of some 70,000 to 320,000 seed per acre, with half to a third of them available for annual seed fall" (Lotan 1975) Mean (n) / Maximum filled seeds per tree "Lodgepole pine (1250 mm annual Rainfall) (*Pinus contorta*) 10 yr 395 (52) /1566; Lodgepole pine (700 mm annual Rainfall) (P. contorta) 10yr 6630 (17) 17353" (Ledgard 2001) average 395/ tree (Ledgard 1996) average 6630/ tree (Ledgard 1996) Seed production: yes, a 12-year-old, 5 tree is capable of producing just under 15,000 viable seeds/year dispersal: wind viability: 79-90%, rarely drops below 70% germination: spring, germination low; 15°C seed bank: delayed germination still occurring after 4 years; will survive 10-20 years in dry storage at 4oC and maintain 79-90% germination (Timmins and Mackenzie 1995) "In one study over a 10-year period in central Colorado and southern Wyoming, the average amount of seed stored in closed cones was 2.5 to 3.5 times greater than the current crop (Bates 1930). The average number of sound seeds stored in closed cones ranged from 181,000 to 1,104,000 per acre." (Alexander 1974) "Lotan (1967a, 1968) studied the variation in serotinous cone habit and estimated the number of sound seeds stored in closed cones on four areas in Montana and Idaho (table 3). Most trees produced almost entirely either open or closed cones. Only 10 to 20 percent of the trees were classified as intermediate. The estimated number of sound seeds stored in closed cones varied from 0.8 to 3.2 million per acre." (Alexander 1974) "Seed production by individual trees and by stands also varies considerably. Seeds from old and new cones together averaged 50,000 per tree in Idaho and 21,000 per tree in Colorado (Clements 1910). Annual variations in seed production on felled trees during a 10-year period (1912-21) ranged from 0 to 135,000 per acre in southern Wyoming, and from 55,000 to 827,000 per acre in central Colorado (Bates 1930). In central Oregon, where the cones are nonserotinous and the total crop is released each year, annual production in uncut stands varied from 178,000 to 572,000 sound seeds per acre during a 3-year period (Dahms 1963). In the other year of the study, only 14,000 seeds per acre were produced. In Montana, annual seedfall in stands with predominately serotinous cones averaged 70,000 sound seeds per acre over a 4-year period (Boe 1956).

Species	Common	Seed production
		Tackle (1964) observed this Montana area for 2 more years and another area nearby for 2 years, and reported average annual release of 65,000 to about 90,000 sound seeds per acre. In similar stands in Alberta, average annual seedfall varied from 10,000 to 30,000 seeds per acre during a 3-year period (Crossley 1955). Most of the seed released in the predominately serotinous stands probably came from non-serotinous cones, and represents only a small proportion of the annual seed production in these stands." (Alexander 1974) "Linear regression showed that tree trunk diameter explained 43.1% of seed produced per tree (r^2 = 0.431; P < 0.001) (Fig. 6). Moreover, by applying the equation obtained by linear regression to the 24 trees examined that had cones, the number of seed produced by all trees estimated from total cone numbers and mean seeds per cone was 483,922, and the calculated number from the regression of seed production against trunk diameter was 479,846, a difference of just 4,076 seed (0.85%). After dividing trees into either young or old trees (with 50 years the divider) a linear regression showed no significant relationship between tree age and number of seeds produced by a tree." (Mukassabi 2012) " 766,900 seeds ha^{-1}" (Mukassabi 2012)
Pinus mugo complex	mountain	Mean (n) / Maximum filled seeds per tree "Mountain pine (P. uncinata) 20yr 1179/ (10) 2467; Dwarf mountain pine (*P. mugo*) 18yr 3769 (10)/ 10461" (Ledgard 2001) average 1179/tree (Ledgard 1996) average 3769/tree (Ledgard 1996) "There was high year to year variability in number of seeds per cone without any obvious effect of plot, but with obvious synchronisation of all plots at least in some years (Fig. 7b). There was also high year to year variability in number of seeds per hectare without any obvious synchronisation of plots (Fig 7c)." (Vacek et al.2013)
Pinus nigra	black, Austrian	Mean (n) / Maximum filled seeds per tree "21yrs 22300 (10) /144956" (Ledgard 2001) "f1 2500 460–5920 Fecundity for adult 1 trees; f2 14160 2500–44280 Fecundity for adult 2 trees" (Buckley et al.2005) "70 seeds/m^2 on mast years and favourable locations, and less than 10 seeds/m^2 on non-masting years and/or altitudinal limits (Lucas-Borja et al., 2011, 2012)" (Calama et al.2017) Average 22300 / tree (Ledgard 1996) Seed production: yes, 0345-1.5 kg seed/hectolitre of cones; 30,000-87,000 seeds/kg (average 57,000) dispersal: wind viability: expected germination 80-90% germination: spring

Species	Common	Seed production
		seed bank: delayed germination still occurs after 4 years in the high country; seed still remains viable after 10 years if stored in a dry place at 4°C. (Timmins and Mackenzie 1995) "Seed production in the study area was markedly bimodal during the studied period 2000–2014, ranging from 2 to 189 seeds m-2 on average (coefficient of variation = 157%)." (Lucas-Borja and Vacchiano 2018) Viable seeds ha-1: 31850 (2001);73060 (2002), 24100 (2003), 6360 (2004), 135370 (total) (Kerr et al.2008)
Pinus ponderosa	Ponderosa	"In a good seed year as many as 852,050 seeds per hectare (345,08O/acre) may reach the ground." (Burns and Honkala 1990) 1136 ± 828 filled seeds/tree/yr (Wall 2008) "The 21 years of seedfall collection in this study have revealed several trends. Total seedfall per hectare has varied considerably from year to year. Seedfall has exceeded 500,000 seeds ha^{-1} in only 4 years: 1983, 1986, 1990, and 1994 in the shelterwood overstory treatment (Figure 2). Intervening years have shown a pattern of decreased seedfall for several years after a good seed year. Less than 100,000 seeds ha-1 were produced in 12 of the 21 years of record. Seed production in a year before a good year was usually quite low. The periodicity of good seed crops was quite consistent from 1981 to 1994, but no good seed years have occurred since. Note that seed production data presented here is from thinned stands and therefore considerably less than what would be expected in fully stocked ponderosa pine forests in the Colorado Front Range. However, year-to-year variation in seed production is probably valid over a wide range of forest densities." (Shepperd et al.2006) Seed fall per acre for openings 30 feet;60 feet;90 feet: 38660; 52406; 46530 (McDonald 1966) Viable seed per ha: 1182870; 2235870,205355,405154 (Keyes and Maguire 2007) Viable seed per tree: 65715,47572,5266,5064 (Keyes and Maguire 2007) "Seed rain ranged from 500,411 viable seeds/ha (estimated for Unit 2 in 1985) to null crops of 1986 and 1987. In addition to the latter two years, the years 1989, 1990, 1991 and 1993 failed to reach the threshold of 50,000 viable seeds/ha." (Keyes and. Manso González 2015)
Pinus muricata	bishop	median $10^{5.7}$-$10^{6.6}$ seeds/ha (total range 0-$10^{7.2}$) (Bisbing et al.2023) "The fact that plot-level total seed density remained relatively consistent with time since fire (Fig. 3), despite these tree-level increases in cone production through time, reflects the strong relationship between plot-level tree density and cones per tree (values log10-transformed; R^2=0.56).With increasing time since fire, the bishop pine stands studied here quickly developed and then maintained an abundant seedbank while transitioning from extremely high tree density with few cones per tree towards lower tree density with many cones per tree (Fig. 4d)." (Bisbing et al.2023)
Pinus pinaster	maritime	"Large differences were found in the number of seeds released from S cones of the O trees compared with the Y trees (Fig. 2b). Seed releasing from S cones increased with rising temperatures. Cone scales of S from both ages began to open releasing seeds at 45 °C, while a small number of seeds were released at temperatures

Species	Common	Seed production
		over 60°C. A total number of 45 seeds per cone was obtained in S cones of Y trees. The number of released seeds from S cones of O trees progressively increased as temperature rose up to 70°C, reaching an asymptotic mean value of 121 seeds per cone. An intermediate number of seeds (74 seeds per cone) were spontaneously released from NS cones of O trees." (Crux et al.2019) O = old, Y = young, S = serotinous, NS = non-serotinous "Primary cone growth was limited by extreme cold events. Absence of precipitation limits secondary growth and hinders final cone ripening. It turns out that seed production and seed rain may be a bottleneck for natural regeneration of *P. pinaster* under low stand densities, especially under extreme climatic scenarios" (Ruano et al.2015b) We can confirm our first hypothesis of a climate-mediated interannual seed production pattern. Specifically, all considered explanatory variables were exclusively related to cone growth and maturation. Rodríguez-Soalleiro et al. (2008) asserted that flowering in *P. pinaster* is affected by light, temperature, precipitation, and drought. We tested the effects of precipitation, wind velocity, and frost as potential surrogates, but none of them was found to be significant in our analysis. Similarly, we did not find any association between climatic variables and seed rain. Apparently, high temperatures may favour cone opening (Nathan et al. 1999; Tapias et al. 2001), although this may refer to serotinous species, and the local provenance of this study is weakly serotinous. (Ruano et al.2015b) "The positive effect of precipitation during the period of secondary cone growth points out that water stress is a limiting factor for seed production in P. pinaster in the Castilian Plateau. These findings coincide with those of Mutke et al. (2005) and Calama et al. (2011) for *P. pinea* in the same area. Also, Calama et al. (2011) observed a negative effect of the number of days with severe frost during the first winter after cone initiation. Interestingly, we found that the higher the minimum temperature in October of the first year was, the lower the predicted number of seeds was." (Ruano et al.2015b) "In the light of the aforementioned findings, a critical question remains unanswered: when considering the temporal dimension, can seed production and seed rain be a bottleneck for natural regeneration of *P. pinaster* in the Castilian Plateau? According to Matney and Hodges (1991), a recruit density of 2000 seedlings·ha^{-1} is the minimum requirement for successful natural regeneration. However, a density of between 1000 and 1500 viable trees·ha^{-1} may be considered to be satisfactory in stands with abiotic stress (Rodríguez-García et al. 2010). Several factors can negatively affect the subsequent stages of the regeneration process after dispersal, namely predation of the dispersed seeds and the limiting climatic conditions occurring in the Mediterranean ecosystems during the initial months of seedling establishment (Miguel Pérez et al. 2008) The impact of predation, germination failure, and seedling survival in the specific case of *P. pinaster* can be analysed by taking other experiments carried out in the same experimental site into account, e.g., Ruano et al. (2015) studied the effect of predation on the belowground seed bank. They observed mean percentages of seed predation of around 75% for control and clear-cutting plots, around 86% for 25% harvest intensity plots, and around 92% for 50% harvest intensity plots. Moreover, Ruano et al. (2009) analysed the effect of harvest intensity and summer water regimes on germination and seedling survival during a period of 18 months. They observed percentages of germination around 40% for clear-cut, control, and 50% harvest intensity plots and

Species	Common	Seed production
		around 60% for a 25% harvest intensity plot. Furthermore, they found percentages of seedling survival of around 13% for a clear-cut plot, around 25% for control and 50% harvest intensity plots, and around 45% for a 25% harvest intensity plot. Taking into account these percentages, it is possible to obtain a rough estimate of the required seed rain to reach the threshold of 2000 seedlings·ha^{-1} for successful establishment. Seed densities of around 5 seeds·m^{-2} for 25% harvest intensity plots, around 9 seeds·m^{-2} for control plots, around 18 seeds·m^{-2} for clear-cut plots, and around 25 seeds·m^{-2} for 50% harvest intensity plots would be necessary to ensure a successful regeneration. According to our results, current seed rain could be enough in the control and 25% harvest intensity plots, even if less favourable climatic conditions occurred. However, natural regeneration may fail in the other cases. The mean predicted seed rain in 50% harvest intensity plots was around 23 seeds·m^{-2}, becoming progressively lower under more extreme climatic events. When clear-cutting is carried out, the seed rain does not seem to be abundant enough regardless of the climatic conditions. In this case, the estimated density of established recruits is lower than 1200 seedlings·ha^{-1} for a seed rain density of 10 seeds·m^{-2}." (Ruano et al.2015b) Seed production: yes, 0.75-1 kg seed/hectolitre of cones; 11,000-15,000 seeds/kg dispersal: wind viability: expected germination 75-90% germination: spring seed bank: delayed germination likely; will survive 10-20 years in storage under 10% moisture content at 5C (Timmins and Mackenzie 1995) In total, we collected 6958 seeds (1677 in Coca and 5281 in Cuéllar), which sum up to annual averages of 14.67 seeds/m2 in Cuéllar (four-year average) and about half that amount (7.21 seeds/m^2) in Coca (three-year average). (Juez et al.2014)
Pinus radiata	Monterey	Mean (n) / Maximum filled seeds per tree "Radiata pine (*P. radiata*) 11yr 914 / (14) 3086" (Ledgard 2001) Seed production: yes, annual dispersal: wind viability: 80% + germination: spring seed bank: delayed germination still occurring after 4 years in the high count (Timmins and Mackenzie 1995) Average 914 / tree (Ledgard 1996)

Species	Common	Seed production
Pinus x attenuata	knobcone	"Stand-level reproductive capacity increased strongly with stand age. Stand-level proportion mature trees ranged from 0 to nearly 100%, with all observations of 0% occurring in stands <10 years and all observations of >90% occurring in stands≥14 years (Fig. 4A). Estimated closed cone density increased by approximately two orders of magnitude between the initial years of reproductive maturity (5–6 years) and 30 years (Fig. 5A). The effect of stand age was mediated by stand density, with contrasting effects on each measure of stand-level reproductive capacity (Figs. 4B, 5B). There were strong negative effects of stand density and its interaction with stand age on proportion mature trees (Fig. 4B). For 10-year-old stands, proportion mature trees was estimated at >50% for low-density stands, compared with<25% for moderate to high-density stands, and the difference increased over time (Fig. 4C). Conversely, there was a strong positive effect of stand density on closed cone density, which declined with stand age (Fig. 5B). For young stands, estimated closed cone density was more than an order of magnitude greater in high-density stands than in low-density stands, but after~20 years, closed cone densities were similar across stands of all densities (Fig. 5C). Effects of regional climate also varied by response variable. Mean growing season precipitation had a strong positive effect on proportion mature trees (Fig. 4B), while mean growing season CMD had no effect on closed cone density (Fig. 5B). Greater soil clay had positive effects on both measures (Figs. 4E, 5D), although this effect was lower magnitude than other significant covariates in each model (Figs. 4B, 5B). Stand-level reproductive capacity did not differ between species (Figs. 4B, 5B; Appendix S5–S7 in the Electronic supplementary material)." (Agne et al.2022) "The number of seeds per cone depended on both cone age and extraction method. For the cones processed at UCB, the percentage of scales open (Mann–Whitney U test = 460.5, P < 0.05) and number of seeds per cone (Mann–Whitney U test = 107.5, P < 0.05) was not significantly different (Table 1). For cones processed at LAMRC, gray cones yielded 178.84 gr of seeds, or a weight-based estimation of 61.3 seeds per cone, whereas the brown cones were much higher at 278.08 gr, or 95.4 seeds per cone. X-ray imaging showed that 40% of these seeds extracted from gray cones were empty compared to 23% for brown cones. Following the purification stage the 300 gray and brown cones combined yielded 381.0 gr of seeds (95.3 gr per bushel of cones) for an estimated 19,500 seeds (23,330 seeds per 0.45 kg [1 lb]), equating to an estimated 65 seeds per cone. Germination rate of a sample of 400 seeds from both brown and gray cones was 80%" (Fry 2013)
Pseudotsuga menziesii	Douglas fir	"Douglas-fir seed crops occur at irregular intervals-one heavy and one medium crop every 7 years on the average; however, even during heavy seed years, only about 25 percent of the trees produce an appreciable number of cones. Trees 200 to 300 years old produce the greatest number of cones." (Burns and Honkala 1990) "Data describing the quantities of seeds that may fall vary widely, but most years are characterized by less than 2.2 kg/ha (2 lb/acre), of which no more than 40 percent is sound." (Burns and Honkala 1990) Mean (n) / Maximum filled seeds per tree "Douglas-fir (Pseudotsuga menziesii) 16yrs 421 (10) / 2792" (Ledgard 2001) Seed production: yes, large numbers, 0.5-1 kg of seed per mature tree, i.e. more than

Species	Common	Seed production
		20,000 viable seeds annually dispersal: wind, gravity viability: 80%+ germination: spring, shortly after dispersal seed bank: seed can remain viable for a few weeks to many years; delayed germination still occurring after 4 years in highcountry (Timmins and Mackenzie 1995) Average 412/tree (Ledgard 1996) Seed fall per acre for openings 30 feet; 60 feet; 90 feet: 13068; 8167; 11375 (McDonald 1966) "Cone abortion at, and shortly after, pollination was high, resulting from a combination of low temperatures and possibly high moisture and populations of microorganisms on cones. Seed potential averaged c75 seeds per cone with 31 filled seed per cone, giving an average seed efficiency of 39%. The major loss of seed resulted from insufficient pollen in the ovules. Other causes were ovule and embryo abortion at various stages of development." (Owens et al.1990) "In the Douglas-fir trees selected for this study, both seed and seed-cone losses significantly reduced seed production. The 39% SEF obtained here is typical for many conifers (Schopmeyer 1974; Owens and Blake 1985) and for outcrossing flowering species (Weins et al. 1987). However, the relative importance of the different causes of seed loss may be quite different in conifers than in flowering plants (Sedgley and Griffin 1989). A summary of the observed and estimated losses that occurred in Douglas-fir is given in Fig. 18. Observed losses include prezygotic ones resulting from no pollination and ovule abortion, whereas observed postzygotic losses result from embryo abortion. Other prezygotic losses such as pollen-nucellar interactions can only be estimated because the observed losses never account for all the seed loss. It is assumed that conifers have a low frequency of prezygotic selection but a well-developed postzygotic selection mechanism through polyembryony. In most flowering plants, however, there are highly developed prezygotic mechanisms (Willson and Burley 1983; Sedgley and Griffin 1989). Our results are similar to observations made in four coastal Douglas-fir seed orchards over 4 years (McAuley 1990). In that study, seed efficiency varied from 16 to 45%-over the 4 years and averaged about 29%. Causes of seed losses were estimated as 15-30% because of ovule abortion, 25-35% resulting from inadequate pollination and late embryo abortion, and 2-44% as a result of insect damage. Seed efficiency and causes of seed losses were quite variable from year to year and from one seed orchard to another. " (Owens et al.1990) Summary of the seed efficiency and the causes of seed losses in four Douglas-fir trees in 1986. "Other prezygotic factors" is an estimate based on measures of all other factors: 39% no pollen, 11% Ovule abortion, 11% other prezygotic factors, 20% embryo degeneration, 39% seed efficiency (Owens et al.1990) "The annual Douglas-fir seed fall on the clearcuts ranged from 300 to 168,800 filled seed per acre (Table 1). In 4 of the 12 years the filled seed totaled 30,000 or more per acre. These heavier crops occurred every 3 years to be followed by a year of negligible seed fall." (Gashwiler 1969)

Species	Common	Seed production
Larix decidua	European larch	Seed production: yes, 0.8-2.5 kg seed/hectolitre of cones; 130,000-170,000 seeds/kg of cones dispersal: wind viability: 20-60% germination expected germination: 20-60% germination expected, spring (Timmins and Mackenzie 1995) All species showed marked annual variation in the average number of cones/trees, but clear patterns of masting, followed by a year of poor cone production, were evident in Norway spruce, larch and silver fir (Online resource 2). In species of the genus *Pinus*, annual fluctuations in cone production were less pronounced, although Pinus cembra had masting events in the Bormio study area where it was the dominant species (Online resource 2)." (Bisi et al.2016)
Larix laricina	tamarack	"Open-grown mature stands 80 years old may produce 3,700,000 to 6,200,000 full seeds/ha in a good year, while closed stands the same age may produce 1,200,000 to 3,000,000 seeds/ha." (Burns and Honkala 1990) "Individuals of both species produced fewer seeds per cone at the treeline site compared to individuals at the forest site; black spruce individuals produced on average 4.5 times fewer seeds per cone, while tamarack individuals produced on average 7 times fewer seeds per cone at treeline compared to within the forest (Fig. 3, Table 1)." (Crofts and Brown 2020)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	"Abundant sound seed were dispersed in the selection and shelterwood cuttings despite the fact that only about 10 percent of the total were sound (table 1). More than 1.4 million sound seed were shed by the shelterwood stand where 3 seed trees were reserved per acre. The selection cutting averaged 14 seed trees per acre and produced more than 4.4 million sound seed per acre." (Boe 1961) "The 22-acre clear cutting received sound seed in proportion on to the number of marginal seed trees and distance from them. The south marginal stand, where the seed trees averaged 20 per acre, produced 3 million sound seed (table 1). The north marginal stand of 12 seed trees per acre yielded 2 million sound seeds per acre. From each timber edge, the seedfall in the clear cutting decreased sharply to an average of 196,000 at the center some 400 feet away. Seed dispersal did not seem to be influenced significantly by any prevailing wind direction. There was a slight trend for sound seed to drop closer to the timber edge than empty seed. At the center of the clear cutting only 4.4 percent was sound, but tl1e sound seed-total seed quotient increased to more than 8 percent at the timbered edge." (Boe 1961)
Sequoiadendron giganteum	Giant redwood	

Species	Common	Seed production
Picea abies	Norway spruce	All species showed marked annual variation in the average number of cones/tree, but clear patterns of masting, followed by a year of poor cone production, were evident in Norway spruce, larch and silver fir (Online resource 2). In species of the genus Pinus, annual fluctuations in cone production were less pronounced, although *Pinus cembra* had masting events in the Bormio study area where it was the dominant species (Online resource 2)." (Bisi et al.2016) The seed-production series showed a positive correlation with the mean temperature in June–July in the preceding year ($r = 0.63$, $P < 0.001$), while a negative correlation was found with the June–July temperature 2 years earlier ($r = -0.70$, $P < 0.001$). This model explained 57% of the variance in the seed production index (Fig. 3A). The result confirms that summer temperatures 1 and 2 years before seed production can be used to explain some of the seed production variations in Norway spruce, at least in Scandinavia (Brøndo 1972; Pukkala 1987; Luomajoki 1993). However, there were important differences between the predicted and observed seed series, especially in correspondence of high seed-production years (Fig. 3A). The same problem is present in the model of Pukkala (1987)" (Selås et al.2002) The mean seed rain density was 245 (SE ± 25) seeds m^2 (i.e., >50 times greater than mean germinant density) but there was a tendency for seed rain to decrease with distance from forest edge ($r = 0.94$, $P < 0.0001$) as reproducing trees were spaced further apart far from the forest edge (Fig. 1c)." (Dovčiak et al.2008)
Picea engelmannii	Engelmann spruce	Of *P. engelmannii*: seed m-2 (SD): 132(250); 73 (168), 34 (56), 56 (134), 187 (346), 92 (194), 129 (285), 68 (153), 96 (213), 70 (180), 113 (325), 156 (480), 160 (536) (Buechling et al.2016)
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	"Eight-year observations of seed traps under a 300-year-old stand on the Priest River Experimental Forest yielded 31,600 grand fir seeds per hectare (12,800 acre) annually." (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	

Species	Common	Seed production
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Crops of 20,000 to 4,600,000 seeds per hectare (8,094 to 1,862,000/acre) have been measured, with a mean of 829,000 seeds per hectare (335,000/acre) for 30 crops" Of *C. obtusa*: "Genetic variation in seed/cone production among clones was studied in a hinoki (*Chamaecyparis obtusa* Endl.) seed orchard containing 25 plus-trees by analyzing the number of cones, the yield of cones and seeds of individual ramets for 5 successive years (1982 to 1986). There was significant variation among clones each year and parental contribution in the seed orchard. Specifically, in the years 1982, 1983, 1984, 1985, and 1986, 20% of the clones produced 37.2, 60.6, 36.0, 44.3, and 44.8% of the total cones, respectively. The size of the crop greatly influenced the parental balance in the resulting seed/cone crops. The product moment correlation coefficients and Spearman's coefficients of rank correlation were small and insignificant between consecutive years, but large and highly significant between alternate years, suggesting the presence of carry-over effects in seed/cone production. The broad sense heritability on a clone mean basis was 0.74 ± 0.15 for the number of cones, 0.72 ± 0.14 for the yield of cones, and 0.68 ± 0.13 for the yield of seeds. The corresponding heritabilities from analyses combined over all years were 0.24, 0.558, and 0.724, respectively. These results indicate that seed/cone production in hinoki is under strong genetic control. Several managerial measures are discussed that maintain the genetic diversity in seed lots used for reforestation, by reducing the variation in seed/cone production among clones and producing seed crops with equal contributions from all parents." (Tang and Ide 2001) of *C. nootkatensis*: "In November 1989, only 35% of the total seeds per cone on wind pollinated trees contained embryos and only 15% contained full-size, mature embryos (Fig. 1). Similarly, in 1990, 29% of the total seeds per cone contained embryos, while 12% contained full-size, mature embryos. In other words, the number of fertilized seeds per cone was three in 1989 and two in 1990, whereas the number of full seeds per cone was one in both 1989 and 1990. Although the total, fertilized, and full seeds per cone was slightly more in 1989 (total, 8.4; fertilized, 2.9; full, 1.3) than in 1990 (total, 7.8; fertilized, 2.3; full, 0.9), this difference was not statistically significant (Table 2). However, the fertilized and full seeds per cone in 1989 and 1990 did vary significantly over four clones (Table 2)." (Anderson et al.2002)
Thuja plicata	western red cedar	"Each mature strobilus usually produces only 3 to 6 seeds, but the strobili are often numerous and heavy seed crops are common. In dry years, cone bearing stands in the interior tend to be on high, moist sites. Average annual seed crops vary from 247,000 to 2,470,000 seeds per hectare (100,000 to 1 million/acre) in coastal forests and from 54,000 to 274,000/ha (22,000 to 111,000/acre) in the interior." (Burns and Honkala 1990)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S4. Seeds per cone

Species	Common	Seeds per cone
Pinus contorta	lodgepole	in NZ, mean = 74 (± 1.2); 10-25 filled seed in North America (Carlin et al.2025) 26 (±15) (McNab et al.2019)
Pinus sylvestris	Scots	27 (±11) (McNab et al.2019) "The number of filled seeds per cone varied between 5 and 47 and the coefficient of variation was 53%. The main source of variation of seed number per cone and mean seed mass was the maternal origin. This effect was independent of the tree isolation or age, which did not affect the number of seeds per cone, nor the mean seed mass per cone (Table 3). The cone height had a significant effect on seed number per cone: higher cones contained significantly more seeds than lower cones (21.6 ± 0.98 vs 17.7 ± 0.98) while cone aspect did not have any significant effect on seed number and mass." (Debain et al.2003) "Using data from the 200 cones sampled per tree, One-Way ANOVA tests showed significantly higher number of seeds produced per cone with increased tree age ($F_{12,2841} = 103.50$; P\0.001), tree height ($F_{18,2841} = 203.23$; $P < 0.001$), and trunk diameter ($F_{14,2841} = 186.69$; $P < 0.001$). Linear regression showed that 40% of the variation in number of seeds produced per cone was explained by the cone length, and there was a significant relationship between cone size and number of seeds produced since bigger cones produced more seeds ($r^2 = 0.40$; $P < 0.001$). Furthermore, within a tree there was a significant relationship between the mean number of seeds produced per cone and the mean cone length ($r^2 = 0.556$; $P < 0.001$). Using a linear regression, 55.6% of the average number of seed produced per cone per tree was explained by the average cone length per tree, with bigger cones producing proportionately more seeds (Fig. 5). By applying the regression equation obtained from the three seasons to five other groups of 30 cones each, not sampled before and randomly selected from season 2 and 3, the difference between estimated and actual number of seeds produced per cone was 3.8 ± 1.59." (Mukassbi et al.2012)
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	"The number of sound seeds per cone in Austrian black pine ranges from 30 to 40, of which 15 to 20 are germinable." (Burns and Honkala 1990) "Individual trees had, on average, a mean of 34 filled seeds per cone, with a range of 4.5–70.7. The mode of the fitted beta distribution, m, was 29.4 with a β parameter of 6.34" (Coutts et al.2012)

Species	Common	Seeds per cone
Pinus ponderosa	Ponderosa	"31 seeds in northern Arizona to 70 in central California." (Burns and Honkala 1990)
Pinus muricata	bishop	Median range (48-63), total sample range 0-154 (Bisbing et al.2023)
Pinus pinaster	maritime	
Pinus radiata	Monterey	120 to 200 (Burns and Honkala 1990)
Pinus x attenuata	knobcone	"The number of seeds per cone depended on both cone age and extraction method. For the cones processed at UCB, the percentage of scales open (Mann–Whitney U test = 460.5, $P < 0.05$) and number of seeds per cone (Mann–Whitney U test = 107.5, $P < 0.05$) was not significantly different (Table 1). For cones processed at LAMRC, gray cones yielded 178.84 gr of seeds, or a weight-based estimation of 61.3 seeds per cone, whereas the brown cones were much higher at 278.08 gr, or 95.4 seeds per cone. X-ray imaging showed that 40% of these seeds extracted from gray cones were empty compared to 23% for brown cones. Following the purification stage the 300 gray and brown cones combined yielded 381.0 gr of seeds (95.3 gr per bushel of cones) for an estimated 19,500 seeds (23,330 seeds per 0.45 kg [1 lb]), equating to an estimated 65 seeds per cone. Germination rate of a sample of 400 seeds from both brown and gray cones was 80%" (Fry 2013)
Pseudotsuga menziesii	Douglas fir	"In a survey of four coastal Douglas-fir seed orchards, over 4 years, the average seed potential per cone was 70, but filled seed averaged only 21 per cone, or about 29% (McAuley 1990)" (Owens et al.1991)
Larix decidua	European larch	
Larix laricina	tamarack	seed per cone (figure 3) ~6seed /cone in forest, ~1 seed/cone at treeline (Crofts and Brown 2020)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	
Sequoiadendron giganteum	Giant redwood	
Picea abies	Norway spruce	184 (±60) (McNab et al.2019)

Species	Common	Seeds per cone
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	
Thuja plicata	western red cedar	"Each mature strobilus usually produces only 3 to 6 seeds (8), but the strobili are often numerous and heavy seed crops are common." (Burns and Honkala 1965)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S5. Seed viability

Species	Common	Seed viability
Pinus contorta	lodgepole	"Lodgepole pine produces viable seed at an early age, commonly 5 to 10 years; germination percentage is as high as that of seed borne by mature trees." (Burns and Honkala 1990) 65.4% ± 10.4% filled seed (Wall 2008) "Although no specifics are given, seed stored in cones on trees for 30 years or more are reported to retain viability according to the Woody Plant Seed Manual (USDA Forest Service 1948). Clements felt that during the first 3 to 5 years, germination may diminish, but beyond 5 years loss in viability is slight." (Lotan 1975) "Seed viability ranged from 50–100% of filled seed, with an average of 83.7% (± 0.9 SE) and was consistent across populations and sites." (Carlin et al.2025) "We measured seed germination and assessed the relationship between cone age and seed viability for serotinous cones on beetle-killed lodgepole pine in eight stands adjacent to four of those wildfires (n = 1160 cones). On average, germination was 34 % with three viable germinants produced per cone. Seed germination declined and the proportion of cones that contained no seed increased across the age range of cones sampled (17–51 yrs at the time of the 2020 wildfires). Germination of seed retained within the canopy seedbank of these long-dead stands was roughly half of that measured on live or recently killed lodgepole pine. Though pre-fire tree mortality from bark beetles can exceed 90 % in this area, serotinous cones on the remaining live trees and cones buried in the soil seedbank will contribute viable lodgepole seeds for tree regeneration on some burned landscapes." (Rhoades et al.2022) "On average, 34 % of the released seeds germinated, yielding 2.7 germinants per cone (Table 3). Seed germination declined from about 40 to 10 % within increasing cone age (Fig. 3). Germination was 39 % with 3.5 germinants were per cone for the youngest age class compared to 27 % and 1.8 germinants per cone for the oldest class. In addition to the 183 cones that contained no seed, 350 of the cones containing seed produced no germinants. The proportion of cones that produced no germinants increased from 24 % in the youngest cone class to 33 and 35 % in the middle and oldest classes, respectively." (Rhoades et al.2022) "Germination and the number of germinants produced per cone varied significantly across the eight sites (Fig. 1; Fig. 4). Overall, germination averaged from 26 to 41 % across all sites. Averaged across age classes, germination and germinant production were highest in CP1 and the two ET sites and were generally lowest in Mull1 and Wms2. For the youngest cone class, germination ranged from 25 to 47 % per cone, yielding from 1.9 to 6.2 seeds per cone. Germination declined by 41 % between the youngest and oldest cone classes in all but the Mull sites where it increased. "(Rhoades et al.2022) Germination = 27.3 + 1.1 * year - 0.029 * year^{-2}; R^2 = 0.70 (Rhoades et al.2022) "Key results: Forest-floor cones had seed with high germination capacity (GC): 82% for embedded (partly buried) closed cones vs. 45% for buried partly open cones. For canopy cones, GC steeply declined about 15 yr after cone maturation and by 25 yr, GC was 50%, compared with 98% in the first year. In the 3y- and 6y-MPB

Species	Common	Seed viability
		stands, seeds from cones that were 7 to 9 yr old had similar GC on dead and living trees; however, seeds from the dead trees had lower vigor than seeds from living trees." (Teste et al.2011b) "Conclusions: We demonstrate for the first time that a serotinous pine can form a viable soil seed bank by cone burial, which may facilitate natural regeneration if a secondary disturbance occurs. Seeds contained in 15-yr-old cones showed a steep decline in viability, which could limit regeneration if there is a long delay before a secondary disturbance." (Teste et al.2011b) Seed viability of forest floor cones: "Germination capacity in closed embedded cones remained high (82%: CI: 75 – 87) and was considerably higher than that of partly open embedded cones and buried cones, regardless of cone openness (Fig. 1A)." (Teste et al.2011b) "Canopy seed viability and cone age — Seed germination capacity of closed cones on 9y-MPB attacked stands declined very slowly over the first 10 to 15 yr, but after 15 yr the GC dropped more rapidly with cone age (Fig. 2A). After 25 yr, canopy cones (all cones on dead trees and closed cones on live trees) had a GC of about 50% (Fig. 2A), and after 37 yr, GC had dropped to 22%." (Teste et al.2011b) Location, Species, Seed Wgt (no./g), Viability (%), Seeding rates: total viable (no./m) viable (no./m) area (kg/ha) Broken River, Lodgepole pine, 239, 80, 82, 66, 1.4 Ribbonwood, Douglas fir, 55, 40, 51, 20, 3.7 Ribbonwood, Corsican pine, 53, 90, 42, 38, 3.2 Ribbonwood, Ponderosa pine, 16, 79, 30, 24, 7.5 (Langer 1993) "Variability in seed quality affects sound seed production. Bates (1930) concluded that the percentage of sound seed was higher in years of good seed production than in years of poor production. Furthermore, more sound seeds were available from current cones than from old cones. On the other hand, a number of studies have indicated little difference in seed quality between new cones and those up to 10 years old (Ackerman 1963, Crossley 1956a, Lotan 1964b). About 50 percent of the stored seed was viable in one study (Lotan 1964b). No data are available for seed from nonserotinous cones." Alexander 1974) "The viability of lodgepole pine is rated good. In a series of 413 uniform tests, an average germinative capacity of about 80 percent was obtained after 41 days at 6 to 10 percent moisture with fluctuating diurnal temperatures of 57° to 83° F (Bates 1930). Lodgepole pine will retain a good germinative capacity for long periods of time if properly stored. The germinative capacity of seed stored in serotinous cones is not seriously reduced even after 50 to 75 years (Clements 1910 , Tackle 1954b). Lodgepole pine seed does not normally require pretreatment, but stratification may hasten germination (Tackle 1954b). In nature, lodgepole pine seed overwinters under the snow and germinates the following spring." (Alexander 1974) 75% (Langer 1993)

Species	Common	Seed viability
Pinus sylvestris	Scots	"Of all the seeds that were extracted from sun-dried fresh cones, 41.6±3.3% (SE) were full and 12.5±1.6% (SE) were viable. Of those seeds that were full, 30.4±3.3% (SE) were viable. Of the seeds that were extracted from oven-dried cones from the first cohort, 46.8± 3.6% (SE) were full. Seed viability in this cohort was significantly associated with the number of seeds that were full (Online Resource 7). The close correspondence between the two factors made it legitimate to use the proportion of full seeds (for which there was a larger sample size) as a proxy for seed viability in order to conduct further analysis. Both seed viability (2nd cohort) and the proportion of seeds that were full (1st cohort) were significantly higher at trees that had short light cones (Online Resource 7)" (Worthy and Hulme 2019) "Viability tests showed that 41.6% of seeds were full, but only 30.4% of full seeds were viable, i.e. only 12.5% of all seeds were viable. This is a low level of seed viability [during years with large high cone crops viability may reach 80–90% with average seed viabilities of 40% (McVean 1963)]. A significantly higher proportion of seeds were both full and viable at trees that had short, light cones with fewer seeds per cone—the opposite of the association between large cones and large, full seeds found for *Pinus pinea* (Calama and Montero 2007). Our finding could imply a life-history trade-of between the ability to produce many, well-defended seeds and the ability to produce many viable seeds. However, trees with these cone traits had lower seed predation by squirrels and cones that are smaller had lower seed predation by birds foraging on open cones. These populations of *P. sylvestris* may have reached a near optimum investment in cone defence. Further increases in cone size might reduce seed predation by crossbills, but would be of little benefit in reducing seed loss to other guilds of seed predators and come at a cost of reduced seed number and viability. Conversely, further investment in chemical defence might be expected to be the target of ongoing selection pressure as higher seed phenolic content is associated with reduced seed losses to all seed predators and shows no trade-off with seed number or viability. This is consistent with trends found for the selection of *P. sylvestris* trees by other herbivores (Iason et al. 2011)." (Worthy and Hulme 2019) "The seed viability was high in both years (97.5% in 1995 and 97.8% in 1996), but the number of viable seeds per cone was considerably lower in 1995 (11.5) compared to the number (16.6) found in 1996." (Karlsson 2000) "The number of viable seeds per cone was lowest 1 or 2 years after release both in 1995 (11.4) and in 1996 (13.5). The differences in number of seeds per cone were not significant. Differences in seed viability were small and insignificant, especially in 1995 when seed viability varied between 97.4 and 98.2% for the three groups compared. In 1996 the lowest estimated seed viability was found in trees that had been released for 1 or 2 years (93.7%), and the highest (97.4%) was in the control trees in forests." (Karlsson 2000) "The germination percentage of Scots pine seed at Wybunbury Moss from Petri dishes was 64.4 ± 5.21% (SE, n = 5). Using the 1% TTC method to investigate the viability of seeds, greater values than presented above were shown in all seed sources. The viability of seeds reached 77.8 ± 2.62% (n = 20) where 20 groups of 5 seeds were randomly sampled over the period of the project." (Mukassabi et al.2012) 70% (Langer 1993)

Species	Common	Seed viability
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	"The number of sound seeds per cone in Austrian black pine ranges from 30 to 40, of which 15 to 20 are germinable." (Burns and Honkala 1990) "Ninety-nine percent germination was obtained from seeds stored 10 years in closed containers at 6.6 percent moisture content (oven dry weight basis) at 0° to 2°C (32° to 36°F). No loss of viability occurred in seeds stored in sealed containers at room temperature after 2 years."(Burns and Honkala 1990) "Seed viability analysis evidenced that on average, (a) over three quarters of all seeds were full, PFseeds = 78.5% (3.3), range 50 to 100%; (b) a very high percentage of these full seeds were viable, VSfs = 96.1% (0.8); (c) three quarters of all seeds were viable, VSts = 75.2% (3.0); and (d) none of these variables, neither PFseeds, nor VSts, nor VSts, were related to the age of the mother tree (Table 1)." (Alejano et al.2019) Location, Species, Seed Wgt (no./g), Viability (%), Seeding rates: total viable (no./m) viable (no./m) area (kg/ha) Broken River, Lodgepole pine, 239, 80, 82, 66, 1.4 Rlbbonwood, Douglas fir, 55, 40, 51, 20, 3.7 Rlbbonwood, Corsican pine, 53, 90, 42, 38, 3.2 Rlbbonwood, Ponderosa pine, 16, 79, 30, 24, 7.5 Mean viability: 0.13 (2001); 0.13 (2002), 0.05 (2003), 0.12 (2004) (Kerr et al.2008) 35% (Langer 1993)
Pinus ponderosa	Ponderosa	"Seeds from trees aged 60 to 160, however, are more viable than those of younger or older trees." (Burns and Honkala 1990) 15.5% ± 10.0% filled seed (Wall 2008) "Seed viability also varied from year to year. Yearly germination tests of seed collected from covered traps revealed that very few seed are viable in years that have produced less than 200,000 seed ha^{-1} (Figure 4). Seed viability in years producing more than 200,000 seed ha^{-1} ranged from 27% to 51%, (mean, 42%) with no apparent relationship between viability and seed production." (Shepperd et al.2006) Location, Species, Seed Wgt (no./g), Viability (%), Seeding rates: total viable (no./m) viable (no./m) area (kg/ha) Broken River, Lodgepole pine, 239, 80, 82, 66, 1.4 Rlbbonwood, Douglas fir, 55, 40, 51, 20, 3.7 Rlbbonwood, Corsican pine, 53, 90, 42, 38, 3.2 Rlbbonwood, Ponderosa pine, 16, 79, 30, 24, 7.5 79% (Langer 1993)

Species	Common	Seed viability
Pinus muricata	bishop	median range 94-98 (total range 64-100) (Bisbing et al.2023)
Pinus pinaster	maritime	"The viability of seeds from S cones (SS) was 89.9 ± 7.7% and that of seeds from non-serotinous cones (SNS) was 38.4 ± 6.1%." (Cruz et al.2019)
Pinus radiata	Monterey	90% (Langer 1993)
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	Location, Species, Seed Wgt (no./g), Viability (%), Seeding rates: total viable (no./m) viable (no./m) area (kg/ha) Broken River, Lodgepole pine, 239, 80, 82, 66, 1.4 Ribbonwood, Douglas fir, 55, 40, 51, 20, 3.7 Ribbonwood, Corsican pine, 53, 90, 42, 38, 3.2 Ribbonwood, Ponderosa pine, 16, 79, 30, 24, 7.5 77% (Langer 1993)
Larix decidua	European larch	52% (Langer 1993)
Larix laricina	tamarack	"Tamarack seed remains viable for 4 years or more when stored in sealed containers at 2 to 5 percent moisture content and -8 to -6C." (Burns and Honkala 1990) "Tamarack seed viability was low across both forest and treeline sites, where on average only around 1 out of every 20 seeds produced germinated (7.20±3.44% viable at the forest site and 4.19±1.34% viable at treeline; Fig. 3). The majority of non-viable tamarack seeds had aborted embryos (83.2±5.99% aborted at the forest site and 94.7±2.17% aborted at treeline; Fig. 3), although low levels of pre-dispersal seed predation did occur (10.7±3.79% seeds consumed at forest site and 5.27±2.17% seeds consumed at treeline; Fig. 3)." (Crofts and Brown 2020)

Species	Common	Seed viability
		"The proportion of viable seed decreased with time from 58% in September 1980 to 5% in January 1981. The percentage of viable seed was greater in the open than under the canopy (73 and 58%, respectively) in September, but was nearly identical (23 and 21%, respectively) from October through May" (Brown et al.1988)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	"One study showed that seed viability increased with the age of parent trees. Maximum seed viability was reached when trees were more than 250 years old" (Burns and Honkala 1990) "Seeds produced by trees younger than 20 years generally were less than 1 percent viable, and seeds from trees more than 1,200 years old were not more than 3 percent viable." (Burns and Honkala 1990)
Sequoiadendron giganteum	Giant redwood	"Estimates of percent germination of seeds removed from green cones range from about 20 to 40 percent" (Burns and Honkala 1990)
Picea abies	Norway spruce	
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	

Species	Common	Seed viability
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	
Thuja plicata	western red cedar	
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S6. Seed mortality and seed predation

Species	Common	Seed mortality and seed predation
Pinus contorta	lodgepole	"Seeds stored in serotinous cones on the tree remain viable for years. Apparently, prolonged viability can be maintained so long as cones or seeds are not in contact with the ground. Once cones are on the ground, cones open. Damping-off fungi may infect the seed, rodents may feed on the seeds, or germination may occur; for the most part, seeds are not stored in the soil." (Burns and Honkala 1990) 29.6% (Wall 2008) "After six years, MPB-killed stands had released 45% of their canopy seed bank through cone opening, cone fall due to breakage, and squirrel predation" (Teste et al.2011a) "Further losses of canopy seed banks are expected with time since we found 9-yr-MPB stands had 38% more open canopy cones. This was countered by the development of a modest forest-floor seed bank (6% of the original canopy seed bank) from burial of cones; this seed bank may be ecologically important if a fire or anthropogenic disturbance reexposes these cones. If adequate levels of regeneration are to occur, disturbances to create seedbeds must occur shortly after tree mortality, before the seed banks are lost." (Teste et al.2011a) "The cones withstand below freezing temperatures and are not generally affected by cone- and seed-feeding insects. Only squirrels and coreid bugs are significant seed predators." (Burns and Honkala 1990) "In the Northern Hemisphere seed predation by squirrels, birds, mice and insects can be significant (Lotan and Perry, 1983; Keeley and Zedler, 1998). (Ledgard 2001) Taken by rodents (SD) (n = 27–30 trees/sample) (Wall 2008) 565.1 ± 784.7 (38.2%) 267.0 ± 369.6 (15.8%) 27.2 ± 42.0 (13.5%) 25.0 ± 60.3 (0.3%) 516.2 ± 618 (37.1%) Taken by birds (SD) (n = 27–30 trees/sample) (Wall 2008) 0.0 ± 0.0 (0.0%) 0.0 ± 0.0 (0.0%) 0.1 ± 0.6 (<0.1%) 0.3 ± 1.0 (<0.1%) 0.1 ± 0.4 (<0.1%) Taken by insects (SD) (n = 27–30 trees/sample) (Wall 2008) 231.3 ± 327.9 (15.6%) 152.4 ± 222.1 (9.0%)

Species	Common	Seed mortality and seed predation
		5.6 ± 5.9 (2.8%) 0.4 ± 1.1 (<0.1%) 4.9 ± 9.9 (0.4%) "In New Zealand, there are no records of predation of lodgepole pine seed in cones, but seed losses can be major after dissemination. Hayward (personal communication) placed groups of 100 seeds in 29 sparsely vegetated montane sites and used diagnostic features of seed remains to estimate predation by birds and mice. Twenty-two sites were predated, 54% by mice (maximum seed loss 100%) and 15% by birds (maximum 50%). Of the five species used in these trials, lodgepole pine was the least affected, possibly due to it having the smallest seed. On mineral soils Ledgard (1979) reported seed losses of 15% to insects and lesser losses to mice." (Ledgard 2001) 6.2% ± 5.9% per day (n = 9) (low rodent numbers) (Wall 2008) 11% ± 12% per day (n = 5) (high rodent numbers) (Wall 2008) "We found that introduced mammals, particularly rodents, were the primary seed predators of invasive conifers." (Carlin et al.2024) "Seed predation pressure was highest in herbicide treated invasive alien conifer forests, indigenous beech forests, and managed pasture containing grazing livestock. Indigenous tussock areas support fewer vertebrate seed predators and as a result are particularly vulnerable to conifer invasion. The majority of seed predation occurs within the first two weeks post-dispersal." (Carlin et al.2024) "The average percentages of seed eaten in each habitat by the end of the experiment for P. contorta and Ps. menziesii respectively were highest in Beech Forest (92.8%; 95.9%), followed by ACCF (91.7%; 82.7%), Pasture (90.7%; 72.4%), GCCA (70.0%; 69.8%), and finally Tussock (52.1%; 31.6%; Fig. 4, 5)." (Carlin et al.2024) "Overall seed predation was significantly lower in tussock habitats (β=−1.03, 95% CI [−1.67, −0.385], p<0.003)." (Carlin et al.2024) "There was no significant overall difference observed between *P. contorta* and *Ps. menziesii* seed predation (β=0.574, 95% CI [−0.631, 1.78], p=0.353), however, significant interactions showed *Ps. menziesii* had lower seed predation rates in pasture and tussock habitats (Pasture: β=−1.69, 95% CI [−3.16, −0.212], p=0.027; Tussock: β=−1.82, 95% CI [−3.17, −0.470], p=0.010)" (Carlin et al.2024) "Specifically, seed predation was highest for the species with the smallest seed (both in terms of mass and volume). 15 days after setting up the experiment *Pinus contorta*, the smallest Pinaceae, was eaten twice as much as the species with the largest seed, *Pinus pinea* (Fig. 1). Seed predation tended to decrease with seed toughness increase (P=0.060 on date 8) but this relationship was not significant. Further, seed predation increased with specific toughness. The species with the highest specific toughness, *Larix decidua*, was eaten three times more than the species with the lowest specific toughness, *Abies nobilis*. Seed volume was the seed trait that best predicted seed predation (highest r2; Fig. 1) [negative relationship]. The three *Abies*

Species	Common	Seed mortality and seed predation
		species are the exception to this pattern, being preyed upon much less than other species of comparable seed mass and volume (Fig. 1; Online Resource 1)" (Moyano et al.2019a) Volume = 8.4 (1.31) (Moyano et al.2019a) "The preferences of the deer mouse (*Peromyscus maniculatus* (Wagner, 1845)), southern red-backed vole (*Myodes gapperi* (Vigors, 1830)), heather vole (*Phenacomys intermedius* Merriam, 1889), long-tailed vole (*Microtus longicaudus* (Merriam, 1888)), and meadow vole (*Microtus pennsylvanicus* (Ord, 1851)) for lodgepole pine (*Pinus contorta* Dougl. ex Loud.), white spruce (*Picea glauca* (Moench.) Voss), and subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) seeds were investigated using cafeteria-style feeding experiments. Seed selection by *P. maniculatus* and *M. gapperi* in the field was also studied. *Peromyscus maniculatus*, *M. gapperi*, *M. longicaudus*, and *M. pennsylvanicus* showed a distinct preference for lodgepole pine seeds and avoidance of subalpine fir seeds, and consumed the different species of seeds in similar relative proportions. *Phenacomys intermedius* behaved very differently from the other rodent species in that it did not show a preference among seed species, and consumed very few seeds in total. Findings from the field seed selection trials were consistent with laboratory results. We suggest that postdispersal seed predation by small mammals could limit the recruitment success of lodgepole pine and white spruce, but would not be a major problem in the regeneration of subalpine fir stands. This could provide an advantage for subalpine fir over neighbouring competitive species." (Lobo et al.2009) Because rodent activity often is equal or lower in forests after fire (Bendell 1974; Borchert et al. 2014), we hypothesized that rodent activity and seed removal would be lower in burned compared to unburned forests. (Frock and Turner 2018) "A total of 3016 out of approximately 19,684 supplied seeds remained in 76 trays as intact seeds (i.e., overall 85% seed removal, which includes in situ granivory of 2407 seeds remaining as hulls (12% of supplied seeds)). Among the 76 stations, seed removal ranged from 11 to 100% (mean = 85% ± 2.7% SE; Table 1a). The percentage of intact seeds remaining in trays did not differ between burned and unburned forests (86% vs. 83% seed removal, respectively; v2 7 = 0.76, p = 0.38) or between 40 and 10 m from the fire's edge (83% vs. 86% seed removal, respectively; v2 7 = 0.12, p = 0.73), and there was no interaction between burn status and distance (v2 7 = 0.07, p = 0.79; Table 2a, Fig. 2a). Rodent activity: During the total 719.8 days of survey time, the 31 cameras recorded a total of 2201 animal detection events. Rodents were detected on 90% of cameras (i.e., on 28 of 31 cameras), with an overall mean detection rate of 3.6 ± 1.9 SE detections per day. Nocturnal rodent activity was approximately twice that of diurnal rodents (mean = 2.4 ± 1.8 SE vs. mean = 1.2 ± 0.7 SE detections per day, respectively; Table 1b) and was lower in burned forests than in unburned forests (0.2 vs. 4.8 detections per day, respectively; F1,7 = 9.807, p = 0.02), but there was no difference in activity between stations at 40 and 10 m from the fire's edge (0.7 vs. 4.5 detections per day, respectively; F1,13= 0.419, p = 0.53) and no significant interaction between burn status and distance (F1,13 = 0.032, p = 0.86; Table 2b, Fig. 2b). Diurnal rodent activity did not differ between burned and unburned forests (2.1 vs. 0.4 detections per day, respectively; F1,7 = 0.079, p = 0.79) or between 40 and 10 m from the fire's edge (0.9 vs. 1.6 detections per day, respectively; F1,14= 0.001, p = 0.97), and there was no significant interaction between burn status and distance (F1,14 = 0.022, p = 0.89; Table 2b, Fig. 2c)" (Frock and Turner 2018)

Species	Common	Seed mortality and seed predation
		Seed removal was high, and, counter to our expectations, did not differ between recently burned and adjacent unburned subalpine forests of the GYE or vary with distance from fire perimeter. Nocturnal rodent activity was lower in burned compared to unburned forests; however, our results suggest diurnal rodents did not avoid lodgepole pine forests that burned at high severity. Although rodent activity was associated with microhabitat conditions in burned and unburned forests, seed removal was not related to any measured microhabitat conditions, and we found no direct correlations between seed removal and rodent activity. Nevertheless, high rates of seed removal suggest animal foraging could affect lodgepole pine recruitment. Similar levels of seed removal and diurnal rodent activity between burned and unburned forests suggest some rodents exhibit behavioral resilience to stand-replacing fires as quickly as 1–2 years after fire. Rodent populations that initially decrease after North American conifer forest fires can return to pre-fire levels in as little as a year (Bond 2015). Because vegetation in the GYE is highly resilient to stand-replacing fire (e.g., Turner et al. 2007; Romme et al. 2011), diurnal rodents may perceive the disturbance-generated edge contrast between burned and unburned forests as inconsequential. For example, even in high-severity fires, little coarse wood (16%) is lost (Tinker and Knight 2000), and this likely provides cover for diurnal rodents in burned forests. While abundances of many rodent taxa are often equal in burned and unburned forests (Griffiths and Brook 2014); other diurnal species are often less abundant in burned forests (e.g., American red squirrels, Podruzny et al. 1999). Nevertheless, our results provide support for the ecological importance of post-disturbance biotic legacies in forest landscapes (Swanson et al. 2011) for diurnal rodents" (Frock and Turner 2018) "Although we did not study the fate of all removed seeds, we have good reasons to believe that the mean of 85% seed removal represents granivory or seed death instead of seed dispersal (Moles et al. 2003), which could enhance lodgepole pine germination. First, 99 percent of stations had evidence of in situ seed consumption in the form of seed hulls equal to 12% of supplied seeds. Second, removed seeds may be cached by animals instead of immediately eaten, but since seed-caching of lodgepole pine seems to be rare (Vander Wall 2003), lodgepole pines are unlikely to benefit from dispersal by animals (Vander Wall 2003). Studies specifically addressing the fate of removed lodgepole pine seeds are needed. However, if we assume removed seeds are consumed or relocated to unsuitable germination sites and the seed removal we observed represents natural conditions, then, at maximum, an average of 15% of seeds were potentially viable after a 28-day study period. In areas where lodgepole pine recruitment might be microsite-limited, this high rate of seed removal could have little to no impact on tree regeneration. However, where seed supply is limiting for recruitment, our results suggest that granivory could depress recruitment of a widespread foundation tree species." (Frock and Turner 2018) "Predation rate was higher at areas located far from the plantations than at sites adjacent to them (X^2 = 14.94, DF = 1, P < 0.001) (Fig. 2). Also, seeds from exotic species were preferred over seeds from native species (X^2 = 24.77, DF = 1, P < 0.001). Seed predators preferred seeds in the following order: Pinus ponderosa (exotic), *Pseudotsuga menziesii* (exotic), *Pinus contorta* (exotic), *A. chilensis* (native), and *N. dombeyi* (native) (Fig. 2). Seed predation was closely related to seed mass; seeds with higher masses were preferred (Table 1). The interaction between species type and distance from the plantation was not significant (X^2 = 4.26, DF = 4, P[0.37). Seed predator exclosures We found significant effects of distance from the plantation (X^2 = 7.85, DF = 1,

Species	Common	Seed mortality and seed predation
		P < 0.005) and the presence of a protective cage (X^2 = 19.93, DF = 1, P \0.001) on seedling emergence. However, we found no differences among tree species in the number of seedlings emerged (X^2 = 2.91, DF = 2, P [0.232), although in areas far from plantations the trend was consistent with the results of the seed removal experiment. The interaction between the two variables (distance and cage) was marginally significant (v2 = 3.00, DF = 1, P < 0.083) (Figs. 3 and 4), and the interactions between species and distance and between species and presence of a protective cage were not significant (X^2 = 0.55, DF = 2, P [0.76; and X^2= 1.49, DF = 2, P[0.47 respectively). Also, the 3-way interaction among the variables was not significant (X^2 = 0.568, DF = 2, P [0.753). Seedling emergence outside cages was four times higher in areas adjacent to plantations than in areas far from them (27 vs. 6 seedlings, respectively), in accord with the results of the seed removal experiment. Emergence in cages was also higher in areas adjacent to plantations than in areas far from them (55 vs. 33 seedlings, respectively) (Fig. 3). This change in proportion of seedling emergence may explain the marginal significance of the interaction terms. In areas near plantations we found only five emerged seedlings in the 300 plots without seed addition, suggesting a minimal effect from natural seed addition in our experiment. From the companion greenhouse study, we obtained seedling emergence rates of at least 85% for all three species. The seed removal experiment and the seed predation experiment produced similar results. Despite the differences in methods, seed predation was more intense in areas farther from plantations and heavier seeds were preferred over lighter ones (Figs. 2 and 4)." (Nuñez et al.2008) "Seed predation has been suggested as an important control of exotic plants, especially when these plants are not superabundant (Maron and Vilá 2001). Our data suggest that seed predators limit the establishment of exotic conifers and retard invasion in our study system. Predation was more intense in uninvaded areas than in areas with high densities of exotic conifers, pointing to a mechanism for the current lack of invasion." (Nuñez et al.2008)
Pinus sylvestris	Scots	"Seed crops in New York and Nebraska have been damaged primarily by coneworm larvae (*Dioryctria* spp.). Tip moths (*Rhyacionia* spp.), which destroy shoots bearing newly formed or developing conelets, are common in Scotch pine seed orchards." (Burns and Honkala 1990) "188.2 ± 37.8 filled seeds m^{-2} that were consumed by crossbills in 1995 and 13.8 ± 7.7 in 1996. Of those seeds that escaped Crossbill predation, 16.2% in 1996 and 51.2% in 1997 were depredated by Tits and Siskins before dispersal" (Castro et al.1999) "Scots pine lost seeds to several types of predators during pre-dispersal as well as post-dispersal periods. Firstly, cones were consumed during the maturation period by the Crossbill, which is an important predispersal mortality factor of many other species of conifers (e.g., Benkman 1993). Considering both the number of seeds ingested by the Crossbill and the values for seed rain in our study years, we estimated that the Crossbill depredated more than 80% of filled seeds each year during seed ripening (seeds consumed seeds consumed + seed rain]). In addition, some species of Tits and Siskins depredated up to 51% of the seeds in newly opened cones surviving the Crossbill attack. This implies that predispersal seed loss is dramatic, greatly decreasing the number of seeds available for dispersal." (Castro et al.1999)

Species	Common	Seed mortality and seed predation
		"After dispersal, Scots pine still lost, in our study sites, a large number of seeds due to predators (Figures 2 and 3). This post-dispersal seed predation ranged from 61% in 1996 (when we used a mixture of filled and aborted seeds similar to the natural proportion) to 96% in 1997 (the year in which we used only filled seeds), values that are equivalent to or higher than those reported previously for vertebrate predation in other coniferous species (Gashwiler 1967, 1970; Radvanyi 1970; Acherar et al. 1984; Johnson and Fryer 1996). Furthermore, both pre- and post-dispersal seed predators actively selected filled seeds (see Vander Wall and Balda 1977; Senar 1981; Jordano 1990; for similar results), increasing the deleterious effect of predators on Scots pine reproduction. As a result, 60 to 67% of filled seeds in cones was reduced to only 0.2 to 0.6% of filled seeds on the ground after the different predation events (Figure 4)." (Castro et al.1999) "Some features of this species reinforce the impact of seed predators on its population regeneration in Mediterranean environments, which are characterized by summer drought, high herbivory pressure, and fire: (1) Scots pine is not able to reproduce vegetatively, being totally dependent on sexual regeneration (Zasada et al. 1992); (2) Seed production in those relict, scattered forests is low, which may make it difficult to satiate predators, increasing the negative effect of predators (Nilsson and Wästljung 1987; Kelly 1994); (3) Since most filled seeds fall directly beneath the canopy of the mother plant, the possibility of escaping in space is strongly limited, and the probability of recolonizing new potentially suitable areas is very low; (4) Seed predation was similarly intense irrespective of the temporal and spatial scale considered, implying that the few seeds dispersed far away probably do not find safe sites either; (5) Scots pine seeds are not dormant and therefore there is no permanent seed bank to buffer the high seed predation; and (6) seedling survival of Scots pine in Mediterranean environments is severely reduced by the dry season (Hódar et al. 1998, see also Arista 1994, García et al. 1999, for other coniferous species in Mediterranean mountains), implying that Scots pine forest regeneration relies heavily on a high number of seeds available to germinate. All these points suggest that predation of Scots pine seeds must be considered a main demographic bottle-neck severely reducing the recruitment probability. This seed predation, together with other factors, causes the expansion of these small, isolated fragments of forest, as well as the natural regeneration within the stands, to be severely constrained in Mediterranean environments." (Castro et al.1999) "Crossbill use of cones was higher for large, broad canopied trees that had many cones (Fig. 3a), for long heavy cones with a high cone-to-seed mass ratio and many seeds per cone (Fig. 3b) and for seeds with low phenolic content (Fig. 3c). However, the variance attributed to Individuals, Locales and residual variation actually increased when the covariates were included, so they were not important in accounting for variation within the data (Online Resource 7). For crossbills, only variation in cone length and the phenolic content of the seed kernel (Fig. 3d, e) resulted in significant variation in cone use among different cohorts and seasons. Cone length was sometimes positively or negatively related to crossbill use, whereas crossbills used seeds proportionally more as the season progressed, during which time seeds matured and kernel phenolic content declined (Table 3).Similarly to crossbills, squirrel use of closed cones was significantly influenced by all main effects except Landscapes (Table 1), although squirrel use was clearly higher in the Locales at Mar Lodge than Abernethy (Table 2), as supported by the covariance parameter values, which were high and indicated

Species	Common	Seed mortality and seed predation
		most variation was attributable to differences among Locales. The highest levels of seed predation by squirrels were at Glen Luibeg and Glen Derry (Table 2). " (Worthy and Hulme 2019) "During May and June, pre-dispersal seed loss to avian granivores from experimental cones was also higher at trees which had longer and heavier naturally occurring cones. However, in July and August, this relationship was reversed with higher seed loss from experimental cones placed at trees with shorter and lighter naturally occurring cones (Cone-factor 2 × Cone-age; $F3 = 5.89$, $p < 0.001$). Seed loss increased for large trees in sparse canopy at Memorial Wood, but decreased elsewhere (Cone-factor 1×Locales; $F7=2.48$, $p<0.0001$, Fig. 5c). Position of cone in the crown determined how Cone-factor 3 affected seed loss. For cones in the crown, seed loss was slightly higher and less variable at trees at high elevation, far from their neighbours with few seeds per cone and low seed mass. The reverse was true for cones attached near the trunk (Cone-factor 3×Position; $F1=7.33$, $p<0.01$) (Fig. 5d)." (Worthy and Hulme 2019) "Predation of seeds in cones by both crossbills and squirrels varied at the Landscapes scale, but for squirrels, predation varied to a greater extent at the Locales, and Individuals scale. Crossbills are highly mobile (Cornelius and Hahn 2012; Jardine 1992) and are likely to be foraging over a wider spatial scale than covered by this study. In contrast red squirrels are territorial, in coniferous areas defending small core ranges of approximately 1–2 ha within larger home ranges of 2–5 ha (Wauters and Dhondt 1992), and thus likely to respond at local spatial scales. However, seed predation by squirrels foraging on fallen cones showed little spatial variation suggesting different foraging strategies for these two resources. Crossbills used more cones in the first cohort studied than in the second, but in both cohorts most cones were utilised between February and June, when seeds would have been mature, but mostly not yet dispersed" (Worthy and Hulme 2019) "Squirrels mostly used cones on trees from the youngest cohort available, switching over to use a new cohort of cones in July. Cone use peaked earlier for the second cohort of cones studied. This was probably due to the summer of 2003 being unusually hot and dry, resulting in atypically early seed fall, causing squirrels to exploit the next cohort of cones sooner and more intensely. This study coincided with a marked decline in the red squirrel population at Abernethy and lower incidence of cone use than had been typically recorded at the same trees in previous years (Summers 2011). Summers (2011) suggests that this population decline may have been due to food scarcity in the previous years, when cone crops had been low. Although this means that the magnitude of cone use recorded in our study is not representative of that over a longer time series, if squirrels are consistent in their tree, cone and seed preferences, our results will still be generalisable" (Worthy and Hulme 2019) "Although pre- and post-dispersal predation can reduce the seed pool of *P. sylvestris* to almost 50% (Worthy et al., 2006) or even over 90% in relict P. sylvestris forests in southern Spain (Castro et al., 1999), it is unlikely to be a serious problem for the regeneration of the species in Sierra de Guadarrama, except in the lower limit, where seed production is much more scarce."(Calama et al.2017) "Worthy et al. (2006) modeled pre- and post-dispersal seed predation for *P. sylvestris* in Scotland and observed how predation rates changed during the regeneration process, from cone production through seed dispersal. However, they observed no important predation effect on belowground seed bank; only about 25 % of seeds were taken by post-dispersal predators." (Ruana et al.2015)

Species	Common	Seed mortality and seed predation
		Only five seedlings emerged in the uncaged plots (Table 2), which were omitted from further analysis; we found remains of seeds depredated by rodents and birds (separated seed coats or bitten seeds) in all plots. For the caged plots, significant differences appeared among treatments for seedling emergence ($F = 35.68$; $df = 2$; 52 $p < 0.0001$; one-way ANOVA). The highest value was recorded in the Disturbed treatment (55.5%), where the seeds were in direct contact with the mineral soil (Table 2). In Control and Clipped treatments many seeds had germinated and expanded the radicle over the ground for some days, but the majority desiccated and died before rooting" (Castroet al.2002) "Most seeds were putatively eaten by seed predators; the percentage varied between 66 and 92 % in the open steppe and 52 and 76% at the forest edge (Fig. 4a)." (Dulamsuren et al.2013) "The results of our sowing and planting experiments suggest that drought, seed predation, and infection by needle-inhabiting fungi are key factors which inhibit the regeneration of Scots pine in Mongolia's foreststeppe ecotone and limit the potential of this tree species to colonize grasslands near to the forest line. The most significant obstacle for seedling emergence was the removal of seeds by seed predators. Losses of 50 to >90 % of the seeds per plot agree with studies on post-dispersal granivory of Scots pine in dry forests in Spain where up to 96 % of the natural seed production that reached the ground were consumed by rodents and birds (Castro et al. 1999). Post-dispersal losses of seeds found in our experiment were in the same order of magnitude as in the other trees species occurring in northern Mongolia, including Siberian larch (Dulamsuren et al. 2008) and Siberian elm (*Ulmus pumila* L.) (Dulamsuren et al. 2009b)." (Dulamsuren et al.2013) "Overall, approximately half of the seeds produced by P. sylvestris were consumed by pre- or post-dispersal seed predators; however, levels of seed predation were highly variable over time. Some of these changes were related to temporal differences in the availability of seeds. There was also a high degree of spatial variation" (Worthy and Hulme 2019) "Seed loss attributed to birds feeding on the experimental open cones was highly variable at every scale and was affected by many factors. More seeds were lost from open cones as the season progressed. The experimental cones may have become more attractive to birds as the number of seeds in other cones and/or the phenolic content of seeds declined. There was little variation in post-dispersal seed predation at the Locales and Landscapes scale. The more accessible the dish (i.e. wider or absent mesh), the higher the seed predation in the majority of months. Seed predation by invertebrates was generally higher than that by vertebrates [consistent with Nystrand and Granstrom (2000), but not Castro et al. (1999)], except for in the colder months, when ants were likely to be inactive (Skinner and Allen 1996) and carabids to have reduced rates of seed consumption (Saska et al. 2010)" (Worthy and Hulme 2019) "Our study shows that mechanical site preparation can lead to high survival rates (80–90%) of planted conifer seedlings on mineral soil sites in Fennoscandia; in general, 15–20 p.u. higher than rates recorded following planting at non-prepared sites (Table 3). Soil inversion and ploughing (few studies) seemed to be associated with somewhat higher MSP-effects and survival rates than patch scarification, disc trenching and mounding. Weaker MSP-effects were also recorded in some of the few studies with lodgepole pine seedlings, but their survival rates were similar to those of Norway spruce and Scots pine seedlings. " (Sikström et al.2020)

Species	Common	Seed mortality and seed predation
		"Altered physical, chemical and biological conditions at forest sites that benefit planted coniferous seedlings in various ways may help to explain the positive effect on survival in our study. Reduction of water stress experienced by seedlings after MSP has been demonstrated on several occasions (Bjor 1971; Grossnickle and Heikurinen 1989; Fleming et al. 1994). However, the effect on soil moisture conditions is sometimes modest (Wetzel and Burgess 2001; Johansson et al. 2005), and each MSP method may have distinct effects on soil moisture. Mounding, for example, creates elevated planting spots that may be associated with enhanced soil drainage, which may be favourable at wet and cold sites but less so under dry and warm conditions (Bassman 1989; Sutton 1993; de Chantal et al. 2003; Löf et al. 2012). Furthermore, exposing the mineral soil bare by removing the humus layer has been found to ameliorate temperature extremes that may occur in the top of the humus layer (Bjor 1971), but increase overall soil temperatures (McMinn 1985; Bassman 1989; Man and Lieffers 1999; Burgess and Wetzel 2000), thereby improving conditions for root growth and establishment. Site preparation also increases minimum air temperatures above the surface, and thus reduces the risk of frost damage (Brække 1972; Blennow 1998; Langvall et al. 2001). However, removal of the humus layer may increase diurnal variations in heat fluxes in the soil, which can increase frost heaving, especially in fine-textured silty soil (Söderström 1973; Bergsten et al. 2001; de Chantal et al. 2007). In the data examined here, the MSP-effect on survival seemed to be independent of the temperature sum (Fig. 3). Below 800 degree days, however, the survival rates were more variable, and were low in the most northerly sites monitored 18 and 25–27 years after planting (Hansson and Karlman 1997; Mäkitalo et al. 2010) (Fig. 2)." (Sikström et al.2020)
Pinus mugo complex	mountain	"Major first year seed and seedling losses resulting from the direct sowing of pine seed on an exposed subsoil at 850 m altitude were attributed to birds (100% unprotected plots), failure of emerging radicle to penetrate the subsoil (15%), insect attack (15%), and frost heave (44%). Losses of lesser significance were caused by mice." (Ledgard 1977) "Open plots" "Within a day of sowing, 10% of the seed had disappeared. after 7 days only 2 seeds of the original 500 sown could be located" (Ledgard 1977)
Pinus nigra	black, Austrian	"For P. nigra in Cuenca mountains three main group of predators were observed (Lucas-Borja et al., 2010): ants, birds (*Fringilla coelebs* L., *Parus caeruleus* L., *Parus major* L.) and rodents (*Apodemus sylvaticus* L., *Mus musculus* L.)." (Calama et al.2017)
Pinus ponderosa	Ponderosa	"In eastern Washington, Idaho, and western Montana, 16 species of insects have been identified as causing seed losses of ponderosa pine. They destroyed up to 95 percent of the cone crop, but most areas sampled suffered losses ranging from 30 to 60 percent. In central Arizona, abortion, ponderosa pine cone beetles (*Conophthorus ponderosae*), and ponderosa pine coneworms (*Dioryctria* sp.) were the three most important causes of cone mortality. Usually the proportion of seeds lost to insects is highest when crops are small." (Burns and Honkala 1990) 33.9% (Wall 2008)

Species	Common	Seed mortality and seed predation
		"Ponderosa pine seeds are consumed by a great many birds and small mammals such as mice, chipmunks, and tree squirrels. In years of low cone production, the potential seed crop may be severely reduced. Squirrels clip many of the cone bearing twigs, destroying flowers and conelets" (Burns and Honkala 1990) Taken by rodents (SD) (n = 27–30 trees/sample) (Wall 2008) 2.7 ± 8.8 (1.4%) 1.3 ± 4.1 (1.4%) -- ± -- (--%) 5.7 ± 20.9 (7.9%) 6.8 ± 23.7 (5.6%) Taken by birds (SD) (n = 27–30 trees/sample) (Wall 2008) 0.0 ± 0.0 (0.0%) 0.0 ± 0.0 (0.0%) -- ± -- (--%) 0.0 ± 0.0 (0.0%) 0.0 ± 0.0 (0.0%) Taken by insects (SD) (n = 27–30 trees/sample) (Wall 2008) 11.1 ± 19.5 (5.9%) 9.6 ± 16.1 (10.6%) -- ± -- (--%) 0.2 ± 0.6 (0.3%) 0.4 ± 1.1 (0.3%) "Ninety-two percent of the sound ponderosa pine seed disseminated before May 3, 1949, was destroyed by rodents and other agents, leaving only 5,800 sound seed per acre available for germination. Douglas-fir seed fared better, losing only 60 percent. Survival of western larch seed was not determined because of the small sampling base. Small mammal population counts and stomach content analyses which were made in the study area indicated that white-footed mice and chipmunks were the principal offenders in seed destruction" (Squillace and Adams 1950) 1.6% ± 0.9% per day (n = 5) (low rodent numbers) (Wall 2008) 34% ± 18% per day (n = 4) (high rodent numbers) (Wall 2008) Volume = 73.5 (6.58) (Moyano et al.2019a) "Propagule pressure was higher than seed predation only at the plantation edge (0 m) and seed predation surpassed propagule pressure at distances of 25 m and further from the plantation (Table 3). Seed predation

Species	Common	Seed mortality and seed predation
		was between 30 and 40% lower at the plantation edge than at distances of 25 m and further from the plantation (Fig. 1)." (Moyano et al.2019b) "Our results provide strong empirical evidence that seed predation may be the most important biotic mechanism limiting P. ponderosa invasions in this system. Seed predators consumed ca. 95% of the seeds dispersed outside the pine plantation, thereby limiting seed availability. Propagule pressure varied in a wide range, from 100 seeds/m² at the plantation edge to 2 seeds/m² at a distance of 200 m from the plantation, however, only at the plantation edge does propagule pressure overwhelm seed predation. At distances of 25 m and further from the pine plantation, seed predation overcame the influence of propagule pressure. This is particularly clear when we consider seed predation in the fixed density transects: at distances from plantation higher than 75 m seed predation was between 25% and 900% higher than propagule pressure. This survival pattern of not predated seeds suggests that P. ponderosa seedling annual recruitment is limited to the first 25 m from the seed source. Altogether, these results provide evidence of how biotic resistance from generalist natural enemies can hinder an invasion" (Moyano et al.2019b) "A consistent pattern of seed consumption by small mammals and birds is revealed by a plot of the number of seeds collected from covered traps against the difference in number of seed that was collected from uncovered traps (Figure 5). A linear equation fit to a zero intercept for this data has a slope of 0.48 (R^2 = 0.92), indicating that on average about 48% of the total seedfall was consumed by animals, regardless of the total seed production in a given year. However, this relationship does not account for the ability of animals to differentially select viable seed. To estimate that effect, we compared the germinative capacity of seed collected from uncovered traps with that collected from covered traps and found that uncovered traps consistently contained a lower percentage of viable seed (Figure 6). A linear equation fit to a zero intercept for this data (R^2 = 0.82) indicates that seed in uncovered traps had only 66% of the germinative capacity of that in covered traps, clear evidence that predatory animals can distinguish viable from nonviable seed. The cumulative effect of seed viability and predation by seed-eating animals can be summarized as follows: Of every 100 seeds produced in good seed years (>200,000 seed ha^{-1}), only 40 were viable. Animals consumed 48% of these, leaving 21 seeds. Because animals could distinguish viable from nonviable seed without eating them, only 66%, or 14, of these seeds remained capable of germinating. Therefore, only 14% of the average total seedfall remained available to germinate after accounting for all of these factors." (Shepperd et al.2006)
Pinus muricata	bishop	
Pinus pinaster	maritime	"Specifically, seed predation was highest for the species with the smallest seed (both in terms of mass and volume). 15 days after setting up the experiment *Pinus contorta*, the smallest Pinaceae, was eaten twice as much as the species with the largest seed, *Pinus pin*ea (Fig. 1). Seed predation tended to decrease with seed toughness increase (P=0.060 on date 8) but this relationship was not significant. Further, seed predation increased with specific toughness. The species with the highest specific toughness, *Larix decidua*, was eaten three times more than the species with the lowest specific toughness, *Abies nobilis*. Seed volume was the seed trait that best predicted seed predation (highest r2; Fig. 1). The three *Abies* species are the exception to

Species	Common	Seed mortality and seed predation
		this pattern, being preyed upon much less than other species of comparable seed mass and volume (Fig. 1; Online Resource 1)" (Moyano et al.2019a) Volume = 58.0 (4.83) (Moyano et al.2019a) "Our results showed that predation reduced the *P. pinaster* belowground seed bank, corroborating what had previously been reported for other pine species in the Mediterranean basin (Castro et al. 1999; Ordóñez and Retana 2004; Zong et al. 2010; Lucas-Borja et al. 2010). Predation was low during the seed rain period, when temperatures were higher, and increased during autumn, as Manso et al. (2014) observed for *P. pinea* in the same study area (northern Castilian Plateau)." (Ruano et al.2015a) "Seed rain was a main explanatory variable in the present work. Our results were similar to those of Lucas-Borja et al. (2010), who analyzed *P. nigra* seed predation in central–eastern Spain. They found less annual seed predation in masting years than in the year with lower seed rain. Regarding climate variability, instead they reported that a climatic variable (accumulated averaged maximum temperatures 20 days before survey date) influenced seed removal percentage." (Ruano et al.2015a) "According to our results, Spanish black pine displayed the best germination performance with 76% of seeds, whereas Aleppo pine obtained the lowest rate (26%). We obtained a higher seedling survival rate for Aleppo pine (12%), followed by Maritime pine and Spanish black pine (seedling survival rates of 11% and 6%, respectively). The treatment that most favoured both emergence and survival was scalping with 62% germination and 13% survival, while the least helpful one was prescribed fire with 35% germination and only 2% survival. For protection from predators, when taking into account all seeds, similar values in germination for this factor were obtained. Finally, survival indicated higher predation outside protection (11% higher in the unprotected plots than in the protected ones)." (Lucas-Borja et al.2018a)
Pinus radiata	Monterey	"Several species of birds and small mammals depend in part for sustenance on the seeds of Monterey pine. Principal bird species are the scrub jay, Stellar jay, and common crow. Important small mammals are deer mice, chipmunks, and ground squirrels. Numerous other creatures eat the seeds of this pine, but their effect usually is insignificant." (Burns and Honkala 1990) "The total proportion of seeds predated averaged across all three seed taxa was 0.04, 0.15, and 0.27 for days 3, 10, and 21, respectively, with the highest proportion predated at 600 m (0.40 by day 21), followed by 1100 m (0.36 by day 21), and the lowest proportion at 900 m (0.05 by day 21). Plates accessible only to invertebrates had the lowest proportion of seeds predated in total and among elevations for all census periods, less than 0.01. Vertebrate plates were predated at proportions of 0.05, 0.21, and 0.37 by days 3, 10, and 21, respectively, while open access plates had the highest proportion of seeds predated of the guild treatments (0.06, 0.23, and 0.39 by days 3, 10, and 21, respectively). For all census periods, the seed taxon with the highest proportion predated was closed-pollinated *P. radiata* (0.05, 0.17, and 0.29 by days 3, 10 and 21, respectively), while closed-pollinated *P. radiata* × *P. attenuata* seeds were predated at a similar proportion to open-pollinated *P. radiata* seeds for all census periods (0.03 and 0.04, respectively by day 3, 0.15 and 0.14, respectively by day 10, and 0.25 and 0.26, respectively by day 21). With respect to microhabitats, the highest proportion of seeds were predated from plates within shrubs by days 3 (0.05) and 10 (0.18), and within

Species	Common	Seed mortality and seed predation
		tussocks by day 21 (0.28), while mixed inter-tussock vegetation had the lowest proportion for all census periods (0.02, 0.11, and 0.25 by days 3, 10, and 21, respectively)." (Gibson 2022) "Specifically, seed predation was highest for the species with the smallest seed (both in terms of mass and volume). 15 days after setting up the experiment *Pinus contorta*, the smallest Pinaceae, was eaten twice as much as the species with the largest seed, *Pinus pinea* (Fig. 1). Seed predation tended to decrease with seed toughness increase (P=0.060 on date 8) but this relationship was not significant. Further, seed predation increased with specific toughness. The species with the highest specific toughness, *Larix decidua*, was eaten three times more than the species with the lowest specific toughness, *Abies nobilis*. Seed volume was the seed trait that best predicted seed predation (highest r^2; Fig. 1). The three *Abies* species are the exception to this pattern, being preyed upon much less than other species of comparable seed mass and volume (Fig. 1; Online Resource 1)" (Moyano et al.2019a) Volume = 30.9 (2.02) (Moyano et al.2019a)
Pinus x attenuata	knobcone	The total proportion of seeds predated averaged across all three seed taxa was 0.04, 0.15, and 0.27 for days 3, 10, and 21, respectively, with the highest proportion predated at 600 m (0.40 by day 21), followed by 1100 m (0.36 by day 21), and the lowest proportion at 900 m (0.05 by day 21). Plates accessible only to invertebrates had the lowest proportion of seeds predated in total and among elevations for all census periods, less than 0.01. Vertebrate plates were predated at proportions of 0.05, 0.21, and 0.37 by days 3, 10, and 21, respectively, while open access plates had the highest proportion of seeds predated of the guild treatments (0.06, 0.23, and 0.39 by days 3, 10, and 21, respectively). For all census periods, the seed taxon with the highest proportion predated was closed-pollinated *P. radiata* (0.05, 0.17, and 0.29 by days 3, 10 and 21, respectively), while closed-pollinated *P. radiata* × *P. attenuata* seeds were predated at a similar proportion to open-pollinated *P. radiata* seeds for all census periods (0.03 and 0.04, respectively by day 3, 0.15 and 0.14, respectively by day 10, and 0.25 and 0.26, respectively by day 21). With respect to microhabitats, the highest proportion of seeds were predated from plates within shrubs by days 3 (0.05) and 10 (0.18), and within tussocks by day 21 (0.28), while mixed inter-tussock vegetation had the lowest proportion for all census periods (0.02, 0.11, and 0.25 by days 3, 10, and 21, respectively). (Gibson 2022)
Pseudotsuga menziesii	Douglas fir	"Animals destroy a large proportion of the seeds" (Burns and Honkala 1990) "Over 60 species of insects are indigenous to Douglas-fir cones, but only a few species damage a significant proportion of the seed crop." (Burns and Honkala 1990) "Here, we investigated seed predation by deer mice (Peromyscus maniculatus) and its effects on recruitment of ponderosa pine (Pinus ponderosa) and Douglas-fir (*Pseudotsuga menziesii*) seedlings in unburned and recently burned fire-adapted montane forests in west-central Montana, USA. Deer mice were almost twice as abundant in burned than unburned stands. Deer mouse removal of seeds from petri dishes was two times higher in burned than in unburned stands, and seed removal levels were 8% higher for ponderosa pine than for the smaller Douglas-fir seeds. In seed-addition experiments, emergence of seedlings in deer mouse-exclusion cages was almost six times higher in burned compared to unburned forest. In both burned and unburned forest, emergence was lower for ponderosa pine than for Douglas-fir. Seedling survival to

Species	Common	Seed mortality and seed predation
		establishment did not differ between conifer species but was considerably higher in burned than in unburned forest. However, effects of seed predation on recruitment prevailed over fire effects: in cages allowing access by deer mice, emergence and establishment were extremely rare for both conifer species in both burned and unburned forest. This research suggests that consumer interactions can substantially influence recruitment even in fire-adapted forest ecosystems." (Zwolak et al.2010) "Estimated abundance of deer mice was 1.6 times higher in burned compared to unburned forest in 2006 (22.6 6 0.9 vs. 14.3 6 0.5 mice/grid, mean 6 SE), and 1.8 times higher in burned compared to unburned forest in 2007 (54.2 6 2.8 vs. 29.5 6 2.7 mice/grid; Table 1)." (Zwolak et al.2010) "Seed removal at night was higher in burned vs. unburned forest, particularly in 2006 (fire and fire 3-year effects; Table 2a, Fig. 1a). In addition, more ponderosa pine than Douglas-fir seeds were removed at night (species effect; Table 2a, Fig. 1a). During the day, overall differences in removal between burned and unburned forest were not significant. However, in contrast to nighttime removal, daytime removal was less intense in burned vs. unburned forest in 2007 (fire 3-year effect; Table 2b, Fig. 1b). As in nighttime trials, removal was greater for ponderosa pine seeds compared to Douglas-fir seeds, though this was only significant in 2007 (species 3-year effect; Table 2b, Fig. 1b)." (Zwolak et al.2010) "Seedling emergence in cages without rodent access was considerably higher in burned vs. unburned stands (fire effect; Table 3), but this effect disappeared in cages with rodent access (rodent access 3 fire effect; Table 3). In cages without rodent access, 39% of seedlings emerged in burned forest vs. 7% in unburned forest, while in cages with access, 0% of seedlings emerged in burned forest vs. 0.9% in unburned forest (Fig. 2a). Overall, seedling emergence was lower for ponderosa pine compared to Douglas-fir (species effect; Table 3). The difference between conifer species was not affected by fire or by mice (fire 3 species and rodent access 3 species interactions were nonsignificant and eliminated from the final model). Seedling survival also differed strongly between burned and unburned forest ($z = 2.72$, $P = 0.006$; Fig. 2b). In 2007, 75% (55 out of 73) of seedlings in burned forest survived until September, whereas survival observed in unburned forest was only 30% (eight out of 27 seedlings survived). In 2008, the overall pattern of higher survival in burned forest remained unchanged, but survival in both burned (30%, 23 out of 76 seedlings) and unburned (0 out of 10 seedlings) forest was lower than in 2007 ($z = 5.48$, $P < 0.0001$). Besides fire and year, no other factors were significant predictors of seedling survival." (Zwolak et al.2010) "In 2007, the proportion of seeds sown that reached the establishment stage when mice were excluded was ~26% for ponderosa pine and 34% for Douglas-fir in burned stands, compared to 1% and 4%, respectively, in unburned stands; mouse access reduced these values to 0% in burned stands and <1% in unburned forest. In 2008, establishment without mice was <1% for ponderosa pine and 16% for Douglas-fir in burned stands, compared to <1% for both species in unburned stands; mouse access reduced these proportions to 0." (Zwolak et al.2010) "The mean daily survival in uncut stands of 0.63 corresponds to 4% of seeds surviving for 1 week, whereas the mean survival of 0.45 in harvested stands would allow only 0.4% to survive for 1 week. These high rates of pine and Douglas-fir seed losses are comparable with rates reported elsewhere for these genera. Pine seeds are preferred by seed predators (Ostfeld et al. 1997; Cornett et al. 1998), and high rates of seed loss have

Species	Common	Seed mortality and seed predation
		been reported for pine in other ecosystems, including 0%–38% survival over 5 months for lodgepole pine in southern and central British Columbia (Sullivan and Sullivan 1982), <1% survival over 2 days for eastern white pine (*Pinus strobus* L.) in oak–pine forests in eastern North America (Plucinski and Hunter 2001), 4% postdispersal survival for Scots pine (*Pinus sylvestris* L.) in southern Spain (Castro et al. 1999), and <1%–20% survival seasonally for Aleppo pine (*Pinus halepensis* Mill.) in burned sites in northern Spain (Broncano et al. 2008). Predation rates reported for Douglas-fir range from 5% survival over 3 days (Sullivan 1979a) or 2 weeks in coastal British Columbia (Sullivan 1979b) to 10% survival in coastal Oregon (Gashwiler 1970). Lower rates are typically reported for other species, including boreal white spruce (Radvanyi 1970; Peters et al. 2004), boreal black spruce (*Picea mariana* (Mill.) BSP; Côté et al. 2003), western larch (*Larix occidentalis* Nutt.) in south-central British Columbia (Stoehr 2000), or coastal western hemlock (*Tsuga heterophylla* (Raf.) Sarg.; Gashwiler 1970), although seed losses are still considered operationally significant in these systems (Spencer et al. 1954; Sullivan and Sullivan 1982). However, generalizations among genera are uncertain because lower rates have also been reported in some pine studies (Nilson and Hjältén 2003; Worthy et al. 2006; Jeffrey pine, *Pinus jeffreyi* Grev. and Balf., Gworek et al. 2007). Broadly, predation rates are often higher in warmer drier situations across the range of species summarized above and within species, e.g., Scots pine (Castro et al. 1999 compared with Nilson and Hjältén 2003; Worthy et al. 2006), Douglas-fir (this study compared with coastal studies by Gashwiler 1970; Sullivan 1979a, 1979b), and lodgepole pine (three study areas of Sullivan and Sullivan 1982). However, there are exceptions (e.g., higher seed survival at lower elevations; Gworek et al. 2007), which emphasize the need for measurements in particular forest types where seed predation is a management concern." (Huggard and Arsenault 2009) "Ninety-two percent of the sound ponderosa pine seed disseminated before May 3, 1949, was destroyed by rodents and other agents, leaving only 5,800 sound seed per acre available for germination. Douglas-fir seed fared better, losing only 60 percent. Survival of western larch seed was not determined because of the small sampling base. Small mammal population counts and stomach content analyses which were made in the study area indicated that white-footed mice and chipmunks were the principal offenders in seed destruction" (Squillace and Adams 1950) "Consumption of Douglas-fir seeds by small forest mammals such as white-footed deer mice, creeping voles, chipmunks, and shrews, and birds such as juncos, varied thrush, blue and ruffed grouse, and song sparrows further reduces seed quantity. A single deer mouse may devour 350 Douglas-fir seeds in a single night. Mouse populations of 7 to 12/ha (3 to 5/acre) are not uncommon" (Burns and Honkala 1990) "Specifically, seed predation was highest for the species with the smallest seed (both in terms of mass and volume). 15 days after setting up the experiment *Pinus contorta*, the smallest Pinaceae, was eaten twice as much as the species with the largest seed, *Pinus pinea* (Fig. 1). Seed predation tended to decrease with seed toughness increase (P=0.060 on date 8) but this relationship was not significant. Further, seed predation increased with specific toughness. The species with the highest specific toughness, *Larix decidua*, was eaten three times more than the species with the lowest specific toughness, *Abies nobilis*. Seed volume was the seed trait that best predicted seed predation (highest r^2; Fig. 1). The three Abies species are the exception to

Species	Common	Seed mortality and seed predation
		this pattern, being preyed upon much less than other species of comparable seed mass and volume (Fig. 1; Online Resource 1)" (Moyano et al.2019a) Volume = 19.3 (1.16) (Moyano et al.2019a) "Overall, seed removal was not very intense in all three habitats. At the end of the experiment, of the 1,200 seeds deployed per species, only 20.5% were removed. There were significant differences between species ($F_{1,9}$ = 6.56, P = 0.03) but not among habitats ($F_{1, 6}$ = 0.84, P = 0.47). There was a significant habitat 9 species interaction ($F_{2,9}$ = 4.15, P = 0.05) indicating that Douglas fir seeds were removed more frequently than silver fir seeds in holm-oak and heathlands, whereas in beech forests this difference was not significant (Fig. 1a). There were differences in seed survival time among habitats (X^2 = 16.48, df = 2, P = 0.0002) and between species (X^2 = 9.19, P = 0.002), being significantly longer in beech forests, followed by holm-oak forests and heathlands. Also, seed survival time of silver fir was longer than Douglas fir (Fig. 1b). Referring to differences within habitats, seed survival time was significantly shorter in Douglas fir than in silver fir in heathlands (X^2 = 8.17, P = 0.004) and in holm-oak forests (X^2 = 9.38, P = 0.002) but not in beech forests (X^2 = 1.07, P = 0.3) (Figs. 1b, 2)" (Carrillo-Gavilán et al.2012)
Larix decidua	European larch	"Specifically, seed predation was highest for the species with the smallest seed (both in terms of mass and volume). 15 days after setting up the experiment *Pinus contorta*, the smallest Pinaceae, was eaten twice as much as the species with the largest seed, *Pinus pinea* (Fig. 1). Seed predation tended to decrease with seed toughness increase (P=0.060 on date 8) but this relationship was not significant. Further, seed predation increased with specific toughness. The species with the highest specific toughness, *Larix decidua*, was eaten three times more than the species with the lowest specific toughness, Abies nobilis. Seed volume was the seed trait that best predicted seed predation (highest r^2; Fig. 1). The three Abies species are the exception to this pattern, being preyed upon much less than other species of comparable seed mass and volume (Fig. 1; Online Resource 1)" (Moyano et al.2019)
Larix laricina	tamarack	"Up to half the tamarack seeds that fall may be destroyed by rodents. As a result of this loss plus that by fungi or bacteria, only 4 to 5 percent of the seed may germinate" (Burns and Honkala 1990) "Snowshoe hares kill many tamarack seedlings in some areas of the Lake States, Alberta, and Alaska. White-tailed deer and moose apparently browse seedlings or saplings to a lesser extent. Porcupines commonly feed on the inner bark and deform the stem or kill the tree. Many tamarack stands have been damaged by this pest in the Lake States, Maine, and eastern Canada. It can be especially damaging in plantations. Red squirrels often cut cone-bearing branchlets, and birds such as the red crossbill occasionally eat the seeds" (Burns and Honkala 1990) Volume = 12.1 (0.65) (Moyano et al.2019a) "In contrast to black spruce, the proportion of consumed tamarack seeds solely responded to the cage treatment, where tamarack seeds under cages were significantly less likely to be consumed; all tamarack seeds not protected by a cage were effectively consumed (Fig. 4, Table 2)" (Crofts and Brown 2020)

Species	Common	Seed mortality and seed predation
Larix occidentalis	western larch	“Ninety-two percent of the sound ponderosa pine seed disseminated before May 3, 1949, was destroyed by rodents and other agents, leaving only 5,800 sound seed per acre available for germination. Douglas-fir seed fared better, losing only 60 percent. Survival of western larch seed was not determined because of the small sampling base. Small mammal population counts and stomach content analyses which were made in the study area indicated that white-footed mice and chipmunks were the principal offenders in seed destruction.” (Squillace and Adams 1950)
Sequoia sempervirens	Coastal redwood	
Sequoiadendron giganteum	Giant redwood	"Birds and mammals exert a negligible effect on giant sequoia seeds on the ground. Sequoia seeds consistently rank at or near the bottom in food preference tests that include seeds of associated species, primarily because they are small and contain little energy" (Burns and Honkala 1990)
Picea abies	Norway spruce	"We addressed species specific, spatial and temporal aspects of post-dispersal seed predation. Seeds of Norway spruce *Picea abies*, European beech Fagus sylvatica, and silver fir *Abies alba* were exposed on dishes in different types of exclosures which allowed access only to specific guilds of seed predators. Removal experiments were carried out in two old-growth forests and a managed forest (macro-sites), including micro-sites with and without cover of ground vegetation. We conducted the experiment in three consecutive years with a mast year of beech and spruce before the first year of the study. The seed removal experiments were combined with live trapping of small mammals being potential seed predators. Our experiments showed a distinctly different impact of different predator guilds on seed survival on the dishes with highest removal rates of seeds from dishes accessible for small mammals. We observed differing preferences of small mammals for the different tree species. Seed survival in different macro- and micro-habitats were highly variable with lower seed survival in old growth forests. In contrast to our assumption, and in contrast to the satiation hypothesis which assumes higher seed survival in and directly after mast years, seed survival was lower in the year following the mast year of beech when a population peak of small mammals occurred and higher in intermast periods when subsequently small mammal population crashed. This suggests a higher importance of sporadic masting shortly after mast years in intermast periods for establishment of forest trees provided that pollination efficiency is high enough in such years. Combined with the high seed mortality observed after the mast year, this corroborates the important role of seed predation for forest dynamics. An altered synchrony or asynchrony of masting of different tree species and changed masting frequencies through climate change may thus lead to strong and non-linear effects on forest dynamics." (Nopp-Mayr et al.2012) "On dishes accessible for small mammals and invertebrates and on dishes with open access we observed variable seed survival rates on day 9 after exposure regarding the tree species and the year. In 2004, no beech seeds remained on the dishes in any sample area at all and mean survival rates of spruce seeds were very low, too (maximum of 9% in the managed forest) (Table 3). Only fir seeds gained higher survival rates ranging from 28% up to 82%. In the following years, seed survival rates were high in the managed forest (87 – 100%) but very diverse in the old-growth forest. In 2005, mean survival rates of spruce and fir seeds were high

Species	Common	Seed mortality and seed predation
		but for beech seeds the average survival rate only ranged from 16% up to 29%. In 2006, when no beech seeds were available, the average survival rate of fi r seeds was high again (92 – 100%) while mean survival rates of spruce seeds were much lower (12 – 28%) (Table 3). Dishes on 30 cm-sticks, constructed to allow mainly birds for seed predation, were in several cases entered by small mammals in 2004 (indicated by indirect signs of small mammal presence such as gnawing signs, faecal pellets, and urine). For data analyses of this treatment, we considered only dishes without indirect signs of small mammals (i.e. 38 out of 45 dishes). Mean seed survival rates on the bird dishes varied to a large extent between areas, years, and tree species. In general, they were high in the managed forest in all years and lowest in the old-growth forest in 2005 (Table 3). In 2004, rodents captured exclosures of small mammals (i.e. dishes with close meshed wire grating) in several cases (4 out of 45 dishes). In the following years, small mammals did not enter close meshed exclosures. For data analyses, we considered only functioning small mammal exclosures. In 2004, on these dishes, only accessible for invertebrates, mean survival rates of seeds were again highest in the managed forest and lower in the old-growth forest. In 2005 and 2006 the average survival rate of seeds was high on every sample area and ranged between 91% and 100% (Table 3)." (Nopp-Mayr et al.2012) "According to the negative binomial regression models for 2004, seed survival rates were significantly enhanced on dishes accessible only for invertebrates in both, model a and b regarding the seed predator guilds (Table 6, 7). In 2005 and 2006 seed survival rates were significantly higher on dishes not accessible for small mammals only in model b (Table 7). In other words, only exclosures of small mammals showed a positive effect on seed survival on the dishes, particularly in the year of high small mammal abundances. Both model a and b (Table 6, 7) illustrate that the tree species had a significant effect on survival rates of seeds: Fir seeds gained the highest regression coefficients in both model types in 2004, representing higher survival rates of these seeds. For the following years, only model b showed significant regression coefficients indicating again higher survival rates of fi r seeds respectively lower survival rates of beech seeds in both years (Table 7). Trapping success, measured in newly captured and recaptured specimens per 100 trapping nights, was correlated with seed survival on dishes accessible for small mammals for each sample area and tree species using nonparametric tests (Kendall's Tau). Correlations were only calculated, where data of both trapping and survival rates of the three years of study were available (i.e. spruce and fir seed survival in the small and large old-growth forest). In all but one cases, trapping rates significantly negatively correlated with seed survival rates on the dishes accessible for small mammals. Only in the large old-growth forest, survival of fir seeds did not correlate with trapping success." (Nopp-Mayr et al.2012) "In the year of highest abundance of small mammals (2004), seed survival rates of all three tree species were higher on the small mammal exclosures, whereas on the dishes accessible for small mammals nearly all spruce and beech seeds were removed within a few days. Thus, in most cases seeds were removed by small mammals before other potential seed predators, such as arthropods or birds, were able to remove them. In the years after the small mammal gradation (2005, 2006) seed survival rates on the small mammal exclosures were never below 90%, indicating that invertebrates have low to moderate influence on average post-dispersal seed loss (cf. Nystrand and Granström 2000). Seed removal from open dishes and from wide wire mesh dishes was approximately equal (Schreiner et al. 2000). This again indicates that substantial parts of seeds are removed by small mammals rapidly and are consequently no longer available for other guilds of predators

Species	Common	Seed mortality and seed predation
		(such as birds or ungulates) (Borchert et al. 1989, Haas and Heske 2005, Iob and Vieira 2008)." (Nopp-Mayr et al.2012)
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Seeds are not a preferred food of rodents in feeding experiments, but harvesting of large numbers of cones and removal of seed from them by rodents have been observed in natural stands" (Burns and Honkala 1990)
Thuja plicata	western red cedar	
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S7. Germination

Species	Common	Germination
Pinus contorta	lodgepole	"Seedling Development-Germination under field conditions is good if climate and seedbed are favorable. Best, germination occurs in full sunlight and on bare mineral soil or disturbed duff, free of competing vegetation." (Burns and Honkala 1990) "Germination is epigeal" (Burns and Honkala 1990) "Adequate soil moisture is required for germination and survival during the critical few weeks following germination. In southwest Montana and southeast Idaho, 75 to 90 percent of a season's total germination occurred during the 2 weeks following snowmelt in late June, when the soil was saturated and temperatures were favorable. Germination can be delayed if cones do not open during the previous summer." (Burns and Honkala 1990) "Although lodgepole pine germinates well on most organic seedbeds, such materials tend to dry faster than mineral soil and seedlings often die in this seedbed. Lodgepole pine seeds have little need for stratification and germination depends largely upon temperature. At optimum temperatures and moisture, almost 100 percent of the seeds germinate rapidly." (Burns and Honkala 1990) "Both shading and competition inhibit germination and survival." (Burns and Honkala 1990) "Lodgepole pine often produces high seed loads (Lotan and Jensen, 1970) that can generate abundant post-fire seedlings (>500,000 ha^{-1}; Turner et al., 2004), so the reduction in seed availability we observed in gray-phase stands may or may not result in unacceptable tree stocking levels (Hansen et al., 2018). Combining the average number of germinants we tallied (3 cone-1), with average tree (1500 t ha^{-1}) and cone density (450 cones t ha^{-1}) in mature lodgepole stands in the Southern Rockies (Lotan and Jensen, 1970; Koch, 1987; Pearson et al., 1987; Ryan and Waring, 1992), we estimate around 2 million germinants ha^{-1} (range: 1 to 3 million ha^{-1}) from gray-phase, serotinous stands. Losses of seed and seedlings to predation, drought, competition, and other factors vary widely (Hansen et al., 2018), though regional estimates indicate that 2500 to 15,000 seeds are needed to produce one seedling on moderate and challenging sites (i.e., dry sites with high competition), respectively (Lotan and Perry, 1983)" (Rhodes et al.2022) "Germination rates reported by several researchers are variable but generally quite high, ranging from 65 to over 90% in laboratory conditions (Lotan and Perry,1983)." (Despain 2001) "Heat treatments did not have a negative effect on the germination of *P. contorta*, but they did on *A. araucana* inhibiting the germination at temperatures over 100°C. These results suggest that when undergoing a fire of high intensity, *P. contorta* has a competitive advantage over *A. araucana* and *N. antarctica*; the seed bank would have more possibilities to survive the effects of a wildfire." (Cóbar-Carranza 2015) Viable seeds of lodgepole pine that survive overwinter normally germinate in the early summer following snowmelt in the central Rockies. Optimum air temperature for germination is about 70° F (Bates 1930). Air temperatures of 70°F are usually reached in early June in the central Rocky Mountains, but snow frequently covers the seedbed until middle or late June. In one study in the northern Rocky Mountains, where seeds were

Species	Common	Germination
		sown in the fall to simulate natural seedfall, 90 percent of the germinating seedlings emerged the first 2 weeks in July following snowmelt in late June (Lotan 1964a). Field germination percentages were 74 to 84 percent for all seedbed conditions — considerably higher than reported for Colorado and Wyoming (Bates 1930). Lodgepole pine is noted for its ability to germinate on burned surfaces after wildfire. Fire releases the seed from serotinous cones, creates a favorable seedbed, and reduces vegetative competition for light and moisture. However, site conditions and intensity of burn, as well as seed supply, influence germination on burned seedbeds. Some areas of the same burn will be overstocked, while other parts will be poorly stocked or nonstocked (Horton 1953, 1955; Stahelin 1943). Germination has also been variable on seedbeds prepared by burning. In Colorado, good germination occurred in full sunlight on seedbeds where slash was burned in small piles (USDA-FS 1943). Good germination occurred on burned seedbeds in Alberta, but mortality on the black surfaces was high in full sunlight (Crossley 1956c). On the other hand, poor germination has been reported on burned seedbeds by Ackerman (1957), Boe (1956), and Crossley (1952). These authors did not indicate, however, whether poor success was due to high temperatures and surface drying, deep layers of loose dry ash, or loss of seed supply when cone- bearing slash was burned. In a greenhouse study, leached burned soil provided the highest germination, but unleached burned soil with a high ash content inhibited germination (Gayle and Gilgan 1951). Germination has usually been better on ex- posed mineral soil and on disturbed duff and mineral soil than on other seedbed types, presumably because of more stable moisture conditions (Ackerman 1962, Bates et al. 1929, Boe 1956, Crossley 1956c, Tackle 1964, Trappe 1959). Germination has frequently been good on the natural forest floor (Boe 1956, Crossley 1956c), but the initial germination is often offset by heavy mortality when the seedbed dries out (Ackerman 1962, Prochnau 1963). The effectiveness of the seedbed is influenced by any factor that affects temperature and moisture, as well as depth of slash and distribution of the slash-borne seed supply. On clear days in early summer, exposed soil surfaces are rapidly dried out and heated to high temperatures. Few seeds can imbibe sufficient water to germinate, and many newly germinated seedlings are killed by stem girdle or drought. Shade either from light slash or a residual overstory reduces excessive heating and drying of the soil surface, thereby improving germination on both burned and mineral soil seedbeds (Crossley 1956c, Day and Duffy 1963). On the other hand, slash may inhibit germination if it is too deep and a mat of needles and fine twigs several inches thick accumulates (Boe 1956, Lotan 1964a, Tackle 1954b). Furthermore, if germination is delayed until late summer rains, the late-germinating seedlings may not harden off before the onset of cold weather (Ronco 1967)" (Alexander 1974) Rangiora 51.7 Craigieburn 23.6 Melrose 0.9 Ribbonwood 6.6 total 20.7 (bc) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > Ponderosa | lodgepole = Scots > larch > Ponderosa (Langer 1993) "From the preceding table, it is evident that seeds from the Holy Cross Forest germinated much more successfully than those from the Targhee Forest. For the former the percentage for seeds of all ages was 55,

Species	Common	Germination
		for the latter 29.5. Seeds from the Targhee Forest germinated nearly 50 per cent better at maturity than at from 3 to 5 years and later. Beyond 5 years, there appeared to be little loss in viability, even in cones 25 years old. Seeds from the Holy Cross Forest germinated as well or even better when several years old as at maturity, though a falling off was apparent at from 12 to 14 years...The seeds from each cone were kept separate throughout the tests. It was found that seeds from different cones showed great variability in germination. Seeds from ten 2-year cones from the Targhee Forest showed 55, 50, 33, 17, 27, 21, 47, 0, 34, and 31 per cent, respectively. Of these cones the five containing more than 17 seeds averaged 37 per cent of germination, while those containing less than 17 seeds averaged 30 per cent. This difference in the viability of seeds from cones containing many and few seeds appeared to be general. " (Clements 1910)
Pinus sylvestris	Scots	"Germination is epigeal" (Burns and Honkala 1990) "Field germination is best under full or partial sunlight. Seedling establishment is best when adequate moisture is available and some shade is present. In northern New York, Scotch pine has established itself rapidly on abandoned old fields on very light soils." (Burns and Honkala 1990) In any case, under the current climate conditions, germination rates in *P. sylvestris* are high, with a great variability between years and sites. For instance, germination rates recorded in the studied area were over 70%, the larger rates obtained during spring and autumn at 1600 m. On the contrary, lower rates of germination were observed at timberline areas (Calama et al., 2015b). (Calama et al.2017) "Although *P. sylvestris* can germinate in many different types of seedbed (Cañellas et al., 2004), the litterfall accumulated increases the depth of organic matter and thus improves microsite conditions for germination (Pardos et al., 2008), except if layer thickness reach values over 10 cm. This result contrasts with previous findings for the species in Central Europe (Hille and den Ouden, 2004), or even in Northern Spain, where soil scarification is recommended, and reflects the particular ecological conditions for the species in the mountains of Southern Europe." (Calama et al.2017) "Seedling emergence was strongly influenced by the vegetation type (Table 2). Only 2–8 % of the sown seeds emerged as seedlings in the open meadow steppe, whereas this rate was 8–20 % in the meadow steppe along the forest edge (Fig. 3). The difference in the seedling emergence between the two grassland types was more pronounced at site A than B, as indicated by the significant interaction between vegetation type and site in the ANOVA (Table 2). The influence of the site increased over time, as was indicated by the significant within-subject effect of the site. Irrigation had no continuous effect on seedling emergence, but the significance of irrigation increased over time, as seedling emergence became higher on watered than non-watered subplots; this was especially true for the forest edge at site A (Fig. 3a; Table 2)." (Dulamsuren et al.2013) "In the case of seed germination-related parameters (germination energy (GE), germination percentage at the end of the test (GP), and germination values (GVCZ and GVDP) significant differences were detected between trees ($p < 0.001$, Table 4), the tree effect accounting for 51 to 66% of the total variability. However, the age of the mother tree was not significant (Table 4, Figure 3). These four parameters were highly correlated ($0.51 < r < 0.96$, $p < 0.002$, $n = 30$), the correlation between GVCZ and GVDP being especially prominent ($r = 0.96$, $p < 0.001$, $n = 30$). We observed the following mean values (SD, range): GE = 61.6% (17.3, 24 to 95); GP = 75.4%

Species	Common	Germination
		(13.6, 33 to 96); GVCZ = 34.0 (12.7, 10 to 56) and GVDP = 46.0 (16.7, 14 to 77). Additionally, the percentage of viable seed (VS) ranged from 60 to 100%" (Pardos et al.2022) "In the case of seed germination-related parameters (GE, GP, GVCZ and GVDP) significant differences were detected between trees ($p < 0.001$, Table 4), the tree effect accounting for 51 to 66% of the total variability. However, the age of the mother tree was not significant (Table 4, Figure 3)."(Pardos et al.2022) "The germination percentage of Scots pine seed at Wybunbury Moss from Petri dishes was 64.4 ± 5.21% (SE, n = 5). Using the 1% TTC method to investigate the viability of seeds, greater values than presented above were shown in all seed sources. The viability of seeds reached 77.8 ± 2.62% (n = 20) where 20 groups of 5 seeds were randomly sampled over the period of the project." (Mukassabi et al.2012) Rangiora 49.0 Craigieburn 20.8 Melrose 1.3 Ribbonwood 9.4 total 20.1 (bc) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > Ponderosa | lodgepole = Scots > larch > Ponderosa (Langer 1993)
Pinus mugo complex	mountain	"From early November until early December nearly all undamaged surface seeds (approximately 70%) of total sown seeds) were observed to germinate." (Ledgard 1977) "Germination energy was strongly positively correlated with germination rate ($r = 0.95$). The mean germination rate over all years was lowest in P1 (51 %) and highest in P4 plot (59 %). The germination rate increased in all plots from 1981 to 1999 and remained more or less stable since1999 (Fig. 8)." (Vacek et al.2013)
Pinus nigra	black, Austrian	"Germination is epigeal" (Burns and Honkala 1990) Studied, species: *P. nigra*, *P. pinaster*, *P. halepensis*, Germination rate: 76 ± 23, 35 ± 26, 26 ± 23, Survival rate: 6 ± 10, 11 ± 20, 12 ± 18, Treatment (Control, Fire, Scalping) Germination rate, 39 ± 31, 35 ± 37, 62 ± 21 Survival, rate, 11 ± 20, 2 ± 7, 13 ± 17, Seed protection (Yes, No) Germination rate, 47 ± 30, 43 ± 35, Survival, rate, 14 ± 19, 3 ± 11 (Lucas-Borja et al.2018a) "The germination energy (GE, defined as the percentage of the seeds germinated within the first week of analysis) and germination percentage at the end of the test (GP), as well as germination values according to

Species	Common	Germination
		Czabator and Djavanshir and Pourbeik (GVCz and GVDP, respectively) were assessed (FAO 1985)... Seed germination–related parameters (GE, GP, GVCz, GVDP) were highly correlated among themselves ($0.81 < r < 0.98$, $p < 0.001$, $N = 17$). The correlation between GVCz and GVDP was so prominent ($r = 0.98$, $p < 0.001$, $N = 17$) that the second attribute has been omitted from Fig. 3. In the case of these four parameters, significant differences were detected between trees ($p < 0.001$, Table 1), the tree effect accounting for 58 to 84% of the total variability, but again the age of the mother tree was not significant (Table 1). We observed the following mean values (SD, range): GE = 67.1% (1.9, 22 to 94); GP = 76.3% (1.7, 41.5 to 100); GVCz = 68.0 (3.9, 10 to 148); and GVDP = 66.5 (3.3, 14.5 to 123). In the same way, the dry mass of a single seed (DM1seed) was positively correlated with GP and GVCz ($0.53 < r < 0.57$, $p < 0.003$, $N = 29$), and SDMF with GP ($r = 0.47$, $p = 0.011$, $N = 29$)" (Alejano 2019) Rangiora 68.5 Craigieburn 17.8 Melrose 4.6 Ribbonwood 1.7 total 23.2 (b) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > Ponderosa | lodgepole = Scots > larch > Ponderosa (Langer 1993)
Pinus ponderosa	Ponderosa	Germination is epigeal (Burns and Honkala 1990) "Moisture stress reduces seed germination as well as initial seedling survival and growth." (Burns and Honkala 1990) "In spite of the clear differences in seedfall between seedtree and shelterwood overstories, natural seedling establishment was more complicated. Overall, more seedlings germinated under shelterwood overstories than under seedtree overstories, regardless of seedbed treatment (Table 1). However, this effect was primarily a result of differences that occurred in 1982 and 1995, years that had the highest numbers of seedlings germinating. Significantly more seedlings germinated on unscarified seedbeds in 1982 than on scarified seedbeds, and significantly more seedlings germinated on the shelterwood/scarified treatment combination in 1995. Otherwise, seedbed treatment had no apparent effect on germination" (Shepperd et al.2006) germination by site: induced erosion pavement = depleted forest soil > natural scree (Wendelken 1963) Rangiora 5.9 Craigieburn 0.4 Melrose 0.2 Ribbonwood 0.03 total 1.6 (e) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > Ponderosa | lodgepole = Scots > larch > Ponderosa (Langer 1993)

Species	Common	Germination
Pinus muricata	bishop	
Pinus pinaster	maritime	"Seed germination in control conditions was affected by cone serotiny, being higher in S than in NS cones. The germination of seeds from NS cones from O trees (control 1) was 13.6%. When these seeds were heated at 45°C for 18 h (control 2) the germination was 20.8%, with no significant differences between treatments (P = 0.161 – Fig. 3). The germination of seeds from S cones of O trees (control 3) and that of seeds from S cones of Y trees (control 4) had comparable values (27.2% and 25.6%, P > 0.05). Significant differences were found between control 1 and control 3, and between control 1 and control 4 (P < 0.05). Contrary to expectations, we found that mother plant age and cone serotiny do not, by themselves, affect P. pinaster seed germination." (Cruz et al.2019) Germination rate (%) by fire severity: high 80.4 (1.8); medium 67.5 (1.7); low 52.5 (0.6); control 72.2 (5.2) (Vega et al.2009) Initial germination success (seedlings seeds by fire severity: high 0.10 (0.02); medium 0.07 (0.01); low 0.20 (0.02) (Vega et al.2009) Studied, species: *P. nigra*, *P. pinaster*, *P. halepensis*, Germination rate: 76 ± 23, 35 ± 26, 26 ± 23, Survival rate: 6 ± 10, 11 ± 20, 12 ± 18, Treatment (Control, Fire, Scalping) Germination rate, 39 ± 31, 35 ± 37, 62 ± 21 Survival, rate, 11 ± 20, 2 ± 7, 13 ± 17, Seed protection (Yes, No) Germination rate, 47 ± 30, 43 ± 35, Survival, rate, 14 ± 19, 3 ± 11 (Lucas-Borja et al.2018a)
Pinus radiata	Monterey	"Germination is epigeal" (Burns and Honkala 1990) Rangiora 90.9 Craigieburn 17.8 Melrose 5.8 Ribbonwood 5.9 total 30.1 (a) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > Ponderosa | lodgepole = Scots > larch > Ponderosa (Langer 1993)

Species	Common	Germination
		"Rook (l966b) germinated unstratified seed (previously in cold storage for several months) on wet filter paper in the dark at different temperatures and observed that the optimum temperature for fastest germination was about 25° C. The seeds required 21 days to germinate at 10°C, 14 days at 16°C, 7 days at 19°C and 28°C, and 5 days at 25°C. However, further work should be done using stratified seed and a wider range of temperatures. " (Rook and Whitehead 1979)
Pinus x attenuata	knobcone	"The number of seeds per cone depended on both cone age and extraction method. For the cones processed at UCB, the percentage of scales open (Mann–Whitney U test = 460.5, P < 0.05) and number of seeds per cone (Mann–Whitney U test = 107.5, P < 0.05) was not significantly different (Table 1). For cones processed at LAMRC, gray cones yielded 178.84 gr of seeds, or a weight-based estimation of 61.3 seeds per cone, whereas the brown cones were much higher at 278.08 gr, or 95.4 seeds per cone. X-ray imaging showed that 40% of these seeds extracted from gray cones were empty compared to 23% for brown cones. Following the purification stage the 300 gray and brown cones combined yielded 381.0 gr of seeds (95.3 gr per bushel of cones) for an estimated 19,500 seeds (23,330 seeds per 0.45 kg [1 lb]), equating to an estimated 65 seeds per cone. Germination rate of a sample of 400 seeds from both brown and gray cones was 80%" (Fry 2013)
Pseudotsuga menziesii	Douglas fir	"Germination is epigeal" (Burns and Honkala 1990) Rangiora 31.4 Craigieburn 6.2 Melrose 20.5 Ribbonwood 17.0 total 18.8 (c) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > ponderosa | lodgepole = Scots > larch > Ponderosa (Langer 1993) "There were significant differences in germination rates between species (F1, 8 = 19.05, P = 0.002), yet none were found among habitats (F2, 6 = 0.22, P = 0.80). Also, habitat 9 species interaction was not significant (F2, 8 = 0.07, P = 0.93). In all habitats, the percentage of seed germination was significantly higher in Douglas fir than in silver fir (Fig. 1c)" (Carrillo-Gavilán et al.2012) "The germination rate across all treatments for Douglas-fir was 17.6%, and survivorship of germinants was 82.8%, with 140 surviving individuals. Repeated-measures tests that found watering treatments were significantly correlated with the timing of germination (p = 0.01); non-watered treatments germinated later than those that received supplemental water (Fig. 2). However, the bi-weekly ambient precipitation inputs were not associated with the timing of germination. Mean germination rates were significantly higher in the watered treatments, with germination 1.8 and 2.2 times higher in the 25% and 50% treatments, respectively, than in the control (drought) treatment (Fig. 3A). Once germinated, however, survival was high (>80%) across the caged control and both watering treatments (Fig. 3B). There were no significant effects of wildlife exclusion on germination or survival, though the mean rate of survival was substantially higher in the caged (81%) than in the uncaged control (59%) (Figs. 3A and 3B). Mean daily maximum temperature at the soil surface had a

Species	Common	Germination
		strong negative association with survival (Fig. 3C). Neither temperature variable was associated with germination rates (Supplementary Table S11)." (Foster et al.2020) "This study provides evidence that Douglas-fir regeneration success is limited by moisture and heat stress, even at the cooler and wetter edge of its range. The timing and amount of germination were significantly increased with watering during an unusually dry and hot growing season. Whereas the warmer temperatures across microsites did not affect germination rates, survivorship was markedly reduced in microsites with higher mean daily maximum temperatures. Together, the combined effects of drought (reduced germination) and warmer temperatures (reduced survivorship) strongly limited early recruitment. These microsite and drought treatment effects were likely more pronounced because of the hotter growing-season temperatures (1.7°C higher than the mean), although these climatic conditions are consistent with future climate projections (Lukas et al. 2018). Whereas complete recruitment failure of Douglas-fir in a hot, dry growing season would be unsurprising in some portions of its range, it is notable that it occurred at the higher elevational (cooler and wetter) end of Douglas-fir's range, precisely where it is predicted to fare well under climate change on the Colorado Front Range (Rehfeldt et al. 2006). If Douglas-fir is unable to recruit under such conditions at its upper elevational limit, the outlook for less drought-tolerant species in such sites is likely to be even poorer." (Foster et al.2020)
Larix decidua	European larch	Rangiora 23.9 Craigieburn 25.8 Melrose 6.1 Ribbonwood 3.3 total 14.8 (d) (radiata > Corsican = lodgepole = Scots | Corsican > Douglas fir > larch > Ponderosa | lodgepole = Scots > larch > ponderosa (Langer 1993)
Larix laricina	tamarack	"Experience in Ontario shows that under optimum conditions, seed collected from vigorous stands in a good seed year has 75 to 90 percent germination" (Burns and Honkala 1990) "Germination is epigeal" (Burns and Honkala 1990) "Seedling emergence on lichen was both delayed and less abundant than on moss or control substrate (Fig. 5, Supplementary material Appendix 2 Table A1). Lichen had the greatest significant effect on time until first germination event for both black spruce and tamarack, where it took over two times longer for black spruce and nearly two times longer for tamarack radicle emergence on lichen than on the control substrate ($t = 8.36$, $p < 0.001$ and $t = 4.75$, $p = 0.0001$ respectively). Moss also slowed the time it took for the first germination event for both black spruce and tamarack relative to the control substrate but lesser so than lichen ($t = 2.55$, $p = 0.018$ and $t = 3.15$, $p = 0.005$ respectively). Similarly, lichen had the greatest effect on seedling emergence where the proportion of emerged seedlings on lichen was very low; on average only 6.32 ± 3.99% of black spruce and 1.8 ± 1.91% of tamarack seeds germinated compared to 82.4 ± 9.15% of black spruce and 52.5 ± 15.8% of tamarack seeds germinated on control substrate ($z = -18.3$, $p < 0.0001$ and $z = -9.62$, $p < 0.001$ respectively). Moss also reduced the proportion of emerged black spruce and tamarack seedlings but had less

Species	Common	Germination
		of an effect than lichen, where on average 25.3 ± 10.3% of black spruce seeds germinated and 9.00 ± 9.36% of tamarack seeds germinated ($z = -15.8$, $p < 0.0001$ and $z = -11.0$, $p < 0.0001$)." (Crofts and Brown 2020) Emergence % (SD) mineral soil 3.8 (1.1); feathermoss 0.6 (0.2); wetland trough 4.4 (2.7); wetland feathermoss 6.0 (1.9); wetland tussock top 4.0 (1.7) (Brown et al.1988)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	The germination rate of redwood seeds is usually low. Poor germination often results from a low percentage of sound seeds (less than 15 percent) rather than from dormancy. (Burns and Honkala 1990) "Sound redwood seed has high viability – an average of 79 percent germinated in all lots tested. The range of sound seed germination, or real germination, in 4 lots of seed without pretreatment during a 42-day test period was 68 to 84 percent." (Boe 1961)
Sequoiadendron giganteum	Giant redwood	"Estimates of percent germination of seeds removed from green cones range from about 20 to 40 percent" (Burns and Honkala 1990) "Trees growing on rocky sites yield seeds with substantially higher germinability than those on bottom lands with deeper soils. Larger seeds germinate in higher percentages than small ones. In tests of cone age, germination increased from 20 percent for seeds from 2-year-old cones to 52 percent for 5-year-old cones, then dropped to 27 percent for cones 8 years of age. Germinability also varies with cone location in the crown, seed position within the cones, and among groves (16). Artificial stratification of seeds for 60 days or more resulted in faster germination, but not in higher germination percent" (Burns and Honkala 1990) "Germination is epigeal" (Burns and Honkala 1990)
Picea abies	Norway spruce	
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	"Under natural conditions, seed germinates on almost any seedbed, but survival may be low." (Burns and Honkala 1990) "Germination is epigeal" (Burns and Honkala 1990)
Abies grandis	grand fir	"In natural stands, germination is quite variable but is seldom greater than 50 percent because of embryo dormancy, insect infestation, and the perishable nature of the seeds. Seeds are often so heavily infested with insects that an entire crop may be classed as a failure" (Burns and Honkala 1990) "In reported tests, germinative capacity ranged from 0 to 93 percent and averaged 50 percent (32). The variability and average grand fir germination are about average for the true firs." (Burns and Honkala 1990)

Species	Common	Germination
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Germination is epigeal" (Burns and Honkala 1990) "Germination ranged from 11 to 44 percent in natural seed fall trapped on the floor of seven forests. Germination of collected seed is often higher, about 50 percent" (Burns and Honkala 1990)
Thuja plicata	western red cedar	"Throughout the range of western redcedar, disturbed mineral soil seedbeds seem to be a major requirement for regeneration from seed" (Burns and Honkala 1990)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S8. Seedling survival

Species	Common	Seedling survival
Pinus contorta	lodgepole	"Drought is a common cause of mortality among first-year seedlings; losses vary with soil type and seedbed condition. Greatest losses occur on soils with low water-holding capacity, and duff and litter. Well decomposed organic material, incorporated in the soil, enhances seedling survival, however. Disturbed mineral soil seedbeds generally produce the best germination and survival. Shading has been demonstrated to help under drought conditions in Wyoming." (Burns and Honkala 1990) "Drought losses usually decline considerably after the first growing season. First-year seedlings are particularly vulnerable because of a relatively shallow root system." (Burns and Honkala 1990) "Young, succulent seedlings may die because of high soil surface temperatures. By 2 to 4 weeks of age, seedlings are able to withstand soil surface temperatures higher than 60°C (140°F), which commonly occur at high elevation sites. Freezing temperatures may kill seedlings either directly or by frost heaving. In much of the range of lodgepole pine, however, frosts occur regularly throughout the growing season and seedlings from different sources vary in frost resistance. The amount of frost heaving varies considerably by soil type, location, and year of occurrence but can cause significant losses." (Burns and Honkala 1990) "Lodgepole pine seedlings are poor competitors and competition from grass is often most detrimental. The Douglas-fir/pinegrass habitat type is one of the most difficult sites for lodgepole pine regeneration, particularly if the regeneration effort is delayed until a firm sod cover is established." (Burns and Honkala 1990) "1 sheep to 2 acres = 15% survival, 0% healthy seedling survival; 1 sheep to 4 acres = 20% survival, 1.5% healthy seedling survival; 1 sheep to 8 acres = 58% survival, 15% healthy seedling survival; ungrazed 94% survival, 63% healthy seedling survival" (Beneke 1967) "Competition from the introduced grasses and clovers was sufficient on its own to prevent seedling establishment." (Beneke 1967) "Lodgepole will establish successfully from seed on unimproved pasture. Grazing however markedly reduces seedling survival and growth." (Beneke 1967) "The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) < European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) < Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993)." (Ledgard 2001) "In seeding trials (not involving lodgepole pine) Davis (1996) reported that 50 ± 100% of losses of pine seedlings were due to rabbits (*Oryctolagus cuniculus*) in the first year after sowing seed in depleted, short tussock grasslands. Belton and Ledgard (1991) found that high populations of rabbits will prevent seedling establishment, and Crozier and Ledgard (1990) noted that they will browse lodgepole pine in preference to other conifers." (Ledgard 2001) "Microsite effects on species' abundance patterns were negligible. Across all plots, white fir regeneration was negatively associated with log (P = 0.007) and rock fragment (P = 0.044) cover. There was no association

Species	Common	Seedling survival
		between regeneration and microsite characteristics in either the moderate or high [fire] severity plots. However, in low [fire] severity plots, lodgepole pine seedlings and saplings were positively associated with percent cover of shrubs, forbs, and grasses (results not shown)." (Pierce and Taylor 2011) "Studies have shown that lodgepole pine becomes established most easily on disturbed seedbeds (Alexander 1966; Lotan 1964), and that method of slash disposal may influence height growth during the first 2 years following planting or direct seeding (Lotan and Perry 1977)." (Perry and Lotan 1977) "Dozer-piled (DP) areas averaged 1,333 trees per ha with 24 percent stocking. (To find trees per acre, multiply per ha value by 0.39). Burned-in-place (BP) areas averaged 645 trees per ha, approximately 30 percent of which was advanced regeneration, with 15 percent stocking. " (Perry and Lotan 1977 "Seed: seedling ratios (seedlings surviving to 1976) for the 3 years of recorded seedfall (1963, 1965, 1968) ranged from 625:1 to 2,160:1 on DP areas, and from 1,876:1 to 6,480:1 on BP sites. Ratios within 8 m of the south timber edge were approximately 10 times higher than beyond, despite the ameliorating effect of shade, which may have benefited competing vegetation more than it did tree seedlings. Nevertheless, in DP areas, 37 percent of seedlings were in this area, reflecting the large amounts of seed falling near the timber edge (fig. 2). Beyond 8 m, seedling density was fairly evenly distributed across the strips. Similar clumping of seedlings near the south timber edge did not occur on BP areas, possibly because of the extremely low number of microsites suitable for seedling establishment on the undisturbed seedbeds." (Perry and Lotan 1977) "Only 3 years out of 14 resulted in significant seedling establishment. These followed one another, resulting in a normal curve of seedling ingress (fig. 3). Crossley (1976) has reported the same pattern on a number of lodgepole pine clearcuts in Alberta: seedling establishment is low in the first few years following harvest, increases rapidly, peaks about the 6th year, then declines rapidly. Although we cannot explain this pattern, it may be related to reoccupation of the site by other vegetation, which provides increasing cover (site amelioration) up to a point, after which competitive effects begin to dominate. Weather variables alone explained very little of the year-to-year variation in seedling establishment" (Perry and Lotan 1977) "Fig. 2 and Table 4 indicate differences in the survival trends of each species as dbh increases that follow an inverted U shape. The deciduous species (i.e. PB and AW) reach a plateau later than SB, FB, and PJ but are similar to PL (lodgepole pine) and SW, and with all species showing reduced survival after the trees exceed pivotal sizes. The effect of competition (i.e. BALT by species groups) on survival varied between species with jack pine being the most affected (average IRF = 0.94) and balsam poplar the least affected (average IRF = 1.00) as BALT increased by one unit (m2 ha-1). For white spruce the stronger negative effect of competition was associated with BALT of the deciduous and spruce/fir groups (IRF = 0.99), whereas BALT of the pine group had IRF values greater than 1.00 (Figs. 3–5)." (Cortini et al.2017) "Overall, 62% of the in-situ pines survived and remained healthy the first two growing seasons in the burn scars (Fig. 1a). Survival was lowest for trees planted in the most recent burn scars (40% in 2000s scars) and highest for the oldest scars (90% in 1960s scars) and increased by about 13% per decade since treatment (r2 = 0.94; p = 0.003). Survival did not differ between trees protected from herbivory by mesh tubes and

Species	Common	Seedling survival
		unprotected trees. Annual height increment also increased with time since treatment (Fig. 1b), by 0.7 cm per decade on average. Total tree height was significantly higher in the 1960s compared to the 2000s scars (18.0 vs 14.8 cm) and the other age classes were intermediate (data not shown)." (Rhoades et al.2021) In our previous study (Rhoades and Fornwalt, 2015), we documented sparse tree colonization along a 50-year chronosequence of medium-sized (10–15 m diameter) slash pile burn scars in clear cut lodgepole pine forests. We also found indicators of severe fire effects due to high combustion temperatures (i.e., reddened and hardened soil, char). In this study, we set out to determine whether soil conditions form a major obstacle to tree regeneration within these burn scars. We found no conclusive evidence that they do. Though burn scars cover <5% of the area within regenerating clear cuts (Rhoades and Fornwalt, 2015), the decades-long vegetation cover type change they create is a poorly understood outcome of forest harvesting and site preparation activities that justified this investigation. Lodgepole pine seedlings planted in burn scars had good survival (~60%) and growth (~6 cm yr^{-1}), and scar soils had higher, not lower, levels of soil nutrients. Like most pines, lodgepole pine tolerate or prefer acidic soils (Danielson and Visser, 1989; Erland and Soderström, 1991), so the neutral to slightly alkaline scars soils (7.2–8.0; Fig. 4a) may not have been optimal. Liming and wood ash addition are known to increase EMF colonization of pines growing in acidic soils (pH < 4.0), but to decrease it in neutral pH soils (Børja and Nilson, 2009; Erland and Soderström, 1991). Though lower soil N supply, plant N uptake and EMF colonization may have contributed to reduced tree growth in scar soils (Table 1), that reduction was not sufficient to prevent trees from becoming established in the scars (Fig. 1). The improved tree growth we observed in the older burn scars in both in situ and greenhouse trials (Figs. 1 and 2) suggests progressive amelioration of the burn scar growing environment." (Rhoades et al.2021) "The density of trees (>2.5 cm DBH) in pile burn openings averaged 366 t ha1 across the time series, 10% of the density in the regenerating forests (Fig. 3a). In the regenerating forest surrounding the pile burn scars, tree density increased rapidly for two decades after harvesting; tree density was highest in units harvested 3 decades ago and declined as expected in the older units (tree density (t ha^{-1}) = 4449 + 5937x 944x^2; r^2 = 0.35; p < 0.001). Lodgepole pine comprised >90% of all trees. Lodgepole pines reached 11 m in height and 12 cm in DBH on average in areas cut during the 1960s. Trees with open cones were noted in regenerating forests. of all age classes. The few trees growing within the pile scars had larger diameter in general than those in the regenerating forests. The density of seedlings and saplings (trees <2.54 cm DBH) was also reduced within pile burn openings (Fig. 3b). Total seedling and sapling density was 496 t ha1 on average, 8–20% of that in regenerating forests and the difference was significant except between the oldest pile openings and stands. The density of the 2 smaller height classes (0–15 cm and 16–76 cm) were 3 times higher in 1960s and 1970s compared to the newer pile openings, though there were no statistically significant trends with time since harvest overall. In the regenerating forests, total seedling and sapling density more than doubled the 2 decades after harvesting and then declined uniformly. The largest height class (>75 cm height and <2.54 cm DBH) comprised 84% of these trees. (Rhoades and Fornwalt 2015) After 3 days of exposure of the P. contorta seedlings to sheep grazing ca. 95% were browsed and the severity of seedling damage (number of browsed branches/total branches per seedling) increased with sheep stocking rate. For treatments 19, 29, 49 and 89, the percent of seedling damage was 79.2, 85.8, 93.8 and 99%

Species	Common	Seedling survival
		respectively (Fig. 1). Whenever the seedling was browsed, the terminal bud was browsed (Table 3.1 for estimated means and 95% HPD interval values, Online Resource 3). After 3 days of sheep browsing, the height of *P. contorta* seedlings was reduced by ca. 78% on average, ranging from seedlings with a mean height of 17.85 (5.5 SD) cm at the beginning of the experiment to a mean height of 3.77 cm (3.4 SD) at the end. All stocking rates produced a strong height reduction of P. contorta seedlings, increasing with level of treatment. Stocking rates at 49 and 89 produced a significantly higher reduction in seedling height than stocking rates of 19 and 29. At the same time, there is no significant difference on height reduction when stocking rate is doubled from 19 to 29 (Fig. 2). On the other hand, increasing sheep stocking rate negatively affected the probability of survival of P. contorta. Estimated probability of survival for treatments 19, 29, 49 and 89 was 56.1, 38.3, 12.7 and 0.8% respectively (Fig. 3, Table 3.2 for estimated means and 95% HPD intervals values, Online Resource 3) (Zamora Nasca et al.2018) Our results show that large mammalian herbivores can control conifer invasion by strongly damaging seedlings, reducing drastically their height and survival. In addition, and consistent with our hypothesis, the results indicate that severity of damage is determined by the stocking rate." (Zamora Nasca et al.2018) On average, pines were consumed more in grassland than in shrubland. The average initial height of the seedlings was 35.97± 0.62 cm (mean ± SE) in grassland and 35.8 ± 0.52 cm (mean ± SE) in shrubland, while the average final height of the seedlings was 25.55 ± 0.64 cm (mean ± SE) in grassland and 29.05 ± 0.58 cm (mean ± SE) in shrubland. The observed proportion of browsed *P. contorta* seedlings (i.e. browsing incidence, number of browsed seedlings/number of seedlings) was 89% in grassland and 56% in shrubland. The probability that a *P. contorta* was browsed, as estimated by the model, was significantly higher in grassland than in shrubland, 93% and 62%, respectively ($z = -6.1$, $P < 0.05$; Fig. 2a; Table 1). Similarly, the observed proportion of terminal buds browsed was 89% in grassland and 55% in shrubland. The probability that a terminal bud was browsed, as estimated by the model, was significantly higher in grassland than in shrubland, 93% and 60%, respectively ($z = -6.26$, $P < 0.05$; Fig. 2b; Table 1). Of the subset of browsed seedlings, the observed proportion of browsed branches per *P. contorta* seedling (i.e. browsing intensity, number of browsed branches/number of branches) was 61% in grassland and 70% in shrubland. The proportion of browsed branches per *P. contorta* seedling estimated by the model was 53% in grassland and 64% in shrubland; the differences were statistically significant ($z = 3.45$, $P < 0.05$; Fig. 2c; Table 1). Of the subset of browsed seedlings, the observed average of relative reduction in seedling height (i.e. initial height - final height/initial height) as a result of sheep herbivory was 32% for grassland and shrubland. The relative reduction in seedling height estimated by the model was similar in both vegetation types: 31% and 29% for grassland and shrubland, respectively ($z = -0.92$, $P = 0.36$; Fig. 2d; Table 1). The probability of survival of *P. contorta* seedlings immediately after the treatment was similar in both vegetation types: 75% and 78% for grassland and shrubland, respectively. The probability estimated by the survival model of *P. contorta* in both types of vegetation was 80% ($z = 0.2$, $P = 0.84$; Table 1.) " (Zamora Nasca et al.2019) Germination and seedling survival (after one winter) of *Pinus contorta* sown on bare subsoil, tussock grassland and under beech forest canopy Germinations (%), Survival (%); subsoil 1000m 30, 0; subsoil 1500m 38, 2;

Species	Common	Seedling survival
		native short tussock 1000m 16, 11; native tall tussock 1500 1, 3; under beech canopy 1000m 7, 0; under beech canopy 1500m 12, 0. (Ledgard 1976) Direct-sown seedling in the field - germination, establishment during the first season, and seedling survival thereafter (particularly during the first winter). Provided that the seed is of good quality, germination appears to present least problems although the governing factors in the high country have not been adequately covered. Prior to and during germination it is possible that mice and birds are causing losses. In fact, the poor result of some past oversowing operations could be partly attributable to this. J. D. Hayward (pers. comm.) has reported seed losses up to 60% within 4 days of sowing at 1000 m in the Wairau catchment, Marlborough. During mid-summer in pilot trials 900 to 1600 m a.s.1. in the Craigieburn Range, mice were at least partly responsible for seed losses of 25 to 50%. Once germination has started, the presence of stones on the soil surface can improve early seedling growth by improving the micro-environment (particularly moisture) around the seedling (Harper et al., 1965), and possibly by providing pressure to assist the seedling radicle to penetrate the subsoil (Dowling et al., 1970). A living vegetative cover, on the other hand, impedes seedling vigour by competing for moisture and nutrients (Miles, 1974). The varying effects of different cover types on seedling growth are at present being investigated to find the most satisfactory degree and types of cover which can be used. For survival over the first winter, the presence of cover is obviously essential to modify the effects of frost heave, and certain exotic grasses and legumes have proved efficient at rapidly producing the cover necessary to protect tree seedlings over winter. On exposed surfaces herbaceous species require added fertiliser (particularly with N and P) in order to attain satisfactory growth levels and, without maintenance fertiliser, any introduced vegetative cover cannot be expected to last for more than 3 years (Dunbar, 1970; 1971). Hence, the aim is to promote rapid initial tree-seedling growth so that the plant is sufficiently well-established to withstand climatic extremes once the protective cover has disappeared. By controlling the application rates of fertiliser, some control can be asserted on grass/legume vigour and thus on the degree of interplant competition. There is obviously much room for practical research on interactions between various types of herbaceous cover, fertilisers, symbiotic miro-organisms (e.g., mycorrhizal fungi) and tree seedlings" (Ledgard 1976) "1. Browsing. Browsing by introduced and wild animals is probably the major influence on the survival of young seedlings in New Zealand. Benecke (1967) demonstrated the effect of different levels of browsing pressure by sheep, showing that a sheep stocking level as low as 0.5 stock units per hectare was enough to significantly depress contorta pine seedling survival. Gibson (1988) found that sheep were far more effective at controlling wildings than cattle. Crozier and Ledgard (1990) tested the palatability of seven conifers to sheep browsing in the field. Two-year-old seedlings were planted and fenced from stock for 10 months. They were then exposed to sheep-browsing for a year, before assessment of browse damage. Corsican pine was the least preferred species followed by Douglas-fir, Scots pine, European larch, contorta pine and ponderosa pine, with radiata pine the most browsed species. In a simulated browsing trial, the same authors (Crozier and Ledgard 1990) found that seedlings could be readily killed by removal of all green foliage before age 2; after that time shoots had become sufficiently woody and robust to make it much harder for browsing animals to remove all needles, and hence ensure mortality." (Ledgard 2003)

Species	Common	Seedling survival
		"In parts of New Zealand, rabbits have had a major effect on vegetation cover (McCaskill 1973), and have had a significant impact on the establishment of young wildings. Davis (1996) looked at the effect of excluding rabbits, birds and insects from young radiata pine seedlings during their first year of growth from seed. Rabbits were clearly the major cause of seedling failure (Fig. 4). Where rabbit numbers have been significantly reduced such as after the arrival of RHD in the late 1990s, all woody seedlings, including wildings, have had a much greater chance of survival." (Ledgard 2003) "2. Competition. Although seedling establishment can be aided by the shade and shelter provided by some types of vegetation cover, the establishment success of wildings generally declines with increasing vegetation competition. Benecke (1967) showed that in ungrazed circumstances no contorta pine seedlings survived more than 18 months in improved pasture, whereas survival after 2 years in unimproved grasslands was 94%. Davis (1989) direct drilled contorta pine seed into improved (sown and fertilised) and unimproved grassland. Forty-seven percent of the viable seed germinated to young seedling stage. In improved grassland no seedlings survived to the end of the first season except where a herbicide treatment was added (75% survival). Seedling survival in the unimproved grassland was 100%. Cattaneo (2002), in a glasshouse pot trial involving contorta pine and Douglas-fir, showed that grass competition significantly reduced the seed germination and early growth of both species, with Douglas-fir performing better than contorta pine in the presence of grass. All the Douglas-fir was inoculated with mycorrhizae. The above results suggested that in spread-susceptible areas surrounding plantations there may be a role for the use of fertilisers to increase the competitive effect of grasses (and probably other plants as well), and in so doing to lower the risk of unwanted wilding spread." (Ledgard 2003) "Species' differences in mortality are also shown by mapping the 95% support limits of the Cgen estimates onto the mortality function (eq. 7) at several levels of recent growth (Fig. 2). Because eq. 7 is nonlinear, significantly different Cgen estimates do not map to significantly different mortality probabilities at all growth rates. At 0.1 mm radial growth, the mortality of red cedar < (western hemlock = fir) < spruce < (lodgepole pine = aspen = cottonwood = birch). At 0.3 mm radial growth, the significantly different groups change to redcedar < (hemlock = fir) < spruce < pine < aspen < (cottonwood = birch). At 0.5- and 0.7-mm radial growth, the same grouping holds except that redcedar = hemlock = fir. Spruce joins the low mortality group by 0.9 mm, pine by 1.5 mm, and aspen by 2 mm radial growth. All species show relatively low mortality at growth rates above 2.5 mm" (Kobe and Cotes 1997) "Most lodgepole pine seedling mortality occurs during the first growing season after germination, but seedlings usually require about 2 to 3 years after germination to become established. The first growing season is considered here to be the period of initial survival, and the second and third growing seasons as the time of seedling establishment. The rate of root growth is an important determinant in the initial survival of lodgepole pine seedlings. The further the root penetrates the soil, the better the chance for the seedling to survive drought and frost heaving. Critical rooting depth depends upon the seedbed type, weather, and soil properties. There is little information on the first-year rooting depth of lodgepole pine other than the growth is slow (Tackle 1961a). Lotan (1964a) excavated a few seedlings less than 8 weeks old in the northern Rocky Mountains, and found roots 5 to 6 inches long on mineral soil seedbeds, 4 inches long on undisturbed duff. Seedlings initially

Species	Common	Seedling survival
		form a weak taproot but it does not persist. The initial root system is stunted or obscured by subsequent lateral root development (Horton 1958). In the undisturbed forest, lodgepole pine seedlings establish most readily in openings on mineral soil such as upturned mounds resulting from windfall. Seedlings will become established on duff, litter, partially decomposed organic matter, or decaying wood if they are under a canopy that provides sufficient light while preventing the seedbeds from heating and drying out. Lodgepole pine seedlings do not become established in significant numbers on any seedbed type under a closed canopy. The same seedbeds are available after logging and slash disposal, but with some additional mineral soil, and burned mineral soil and mineral soil mixed with organic matter. Removal of the overstory modifies the microhabitat, however, and such factors as organic seedbeds and competing vegetation frequently become limiting to natural regeneration success. Seedbed preparation to create a more favorable moisture source can modify limiting factors sufficiently to enable seedlings to survive." (Alexander 1974) "The moisture condition of the seedbed during the growing season largely determines first- year seedling survival. In the Rocky Mountains, summer drought can be a serious threat to seedling survival and establishment on some sites. For example, mortality to both natural and planted seedlings on south slopes in northern Wyoming has been attributed largely to drought. In Montana and Idaho, approximately 90 percent of the first-year seedling mortality in one study was caused by drought (Lotan 1964a). On the other hand, Ronco (1961b, 1967) observed the survival of newly germinated and planted seedlings over a period of years, and concluded that drought was not a serious cause of mortality in the subalpine of central Colorado. However, his studies were at a higher elevation in the spruce-fir zone where moisture is generally more abundant. Precipitation during the growing season is particularly critical to the survival of seedlings. Lotan (1964a) found that from 50 to 70 percent of the total mortality in 1 year occurred between June 22 when germination started and July 13, a period when precipitation was negligible. Mortality was substantially reduced after more than 1 inch of rain fell beginning on July 13. The relatively few losses to drought recorded by Ronco (1961b, 1967) were attributed to frequent showers after germination began or seedlings were planted. Summer precipitation is not always a benefit to seedling survival and establishment, especially if storms are so intense that most of the moisture runs off and soil movement on unprotected soil surfaces either buries the tops or uncovers the roots of seedlings." (Alexander 1974) "Most studies of lodgepole pine regeneration have indicated that competing vegetation is a major constraint to successful establishment (Ackerman 1962, Boe 1956, Crossley 1956c, Lotan and Dahlgreen 1971, Tackle 1964). No benefits from understory vegetation of the kind that would provide protection for newly germinated seedlings has been reported." (Alexander 1974) "In other words, early invasion pattern is compatible with the expectations of a spatial process that distributes individual pine recruits at random, with density varying as a function of a covariate (e.g., distance to afforestation in our case). This finding concurs with the idea that early invasions depend more on seed pressure than on the biotic and abiotic relationships that arriving seeds establish with the ground surface components, including plant–plant" (Pauchard et al.2016) "Mortality, which varied on an individual-plot basis from 0% to 66%, is of real concern in this study. The two main causes of mortality (Johnstone 1981a) are shoe-string root rot (*Armillaria mellea* (Vahl. ex Fr.) Kummer)

Species	Common	Seedling survival
		and small-mammal girdling (i.e., snowshoe hares, *Lepus americanus*, and red squirrels, *Tamiasciurus hudsonicus*,). Damage and mortality are localized within the experiment, thus resulting in the significant differences among blocks within sites. An analysis of variance indicated that mortality was not related to spacing, but was significantly higher on the most productive site than on the low site. A large proportion of the sample trees have also been infected by western gall rust (*Endocronartium harknessi* (J. P. Moore) Y. Hiratsuka), which not only reduces tree growth and quality, but which also increases the risk of snow or wind breakage. (Murray 1983)
Pinus sylvestris	Scots	The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) < European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) <Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993). (Ledgard 2001) "Despite high rates of seed germination and seedling emergence, the regeneration occurs as a temporary pulse of seedlings, due to seedling mortality that could be close to 100% after a hot and drought summer (Calama et al., 2015a)." (Calama et al.2017) With respect to light requirements, although in the Eurosiberian forests *P. sylvestris* behaves as a light demanding species, results from different studies in central Spain, suggest the preference of the species to moderate light conditions, at least during the early stages of growth (Pardos et al., 2008; Calama et al., 2015a). (Calama et al.2017) Once emerged, seedlings protected by wire cages had significantly longer survival rates, consistent with our expectations and indicating the important role of herbivores in killing young trees." (Lucas-Broja et al.2018) *Pinus sylvestris* browse-induced mortality: (montane) 0.08 (subalpine) 0.09 lack of adaptation (montane) 0.24, (subalpine) 0.40 other (montane) 0.04, (subalpine) 0.15 (Ameztegui and Coll 2015) Montane belt (% Browsed seedlings, % Lethality); Subalpine belt (% Browsed seedlings, % Lethality); Average (% Browsed seedlings, % Lethality) *Abies alba* 12.5, 77.8; 23.6, 70.6; 18.1, 73.1 *Betula pendula* 65.0, 55.6; 63.9, 56.5; 69.4, 56.0 *Pinus sylvestris* 11.1, 62.5; 18.1, 69.2; 14.5, 66.7 *Pinus uncinata* 9.8, 85.7; 12.5, 77.8; 11.1, 81.2 (Ameztegui and Coll 2015) "At the microhabitat level we found, as expected, the browsing-induced mortality of *P. uncinata* and *A. alba* to decrease when seedlings were growing close to a shrub. The role of shrubs as facilitators of tree regeneration has been widely observed in mountain areas, where shrubs act as 'biotic refuges' for seedlings (Heuze et al., 2005; Milchunas, 2002; Vandenberghe, 2007). In Mediterranean mountains, habitat amelioration has been

Species	Common	Seedling survival
		pointed out as the main mechanism behind this facilitative effect (Castro et al., 2004; Gómez-Aparicio and Canham, 2008). This was also observed in a previous work conducted in the same area, in which we found a protective role of shrubs on seedlings face to adverse climatic events (Ameztegui and Coll, 2013). The results of the present study indicate that, in addition to habitat amelioration, shrubs also increase plant survival by providing physical protection from herbivores, denoting that both mechanisms co-occur in Mediterranean mountain systems (as also found by Boulant et al., 2008)." (Ameztegui and Coll 2015) "Browse-induced mortality rate during winter (i.e. caused exclusively by ungulates) was similar to browse-induced mortality observed during summer, when plots can be frequented by both wild ungulates and domestic livestock. However, intra-guild competition was probably occurring in the study area during summer, when the presence of cattle forced the ungulates to take refuge in the rocky slopes located above the main grazing areas. Thus, assuming that most of the summer browsing-induced mortality is caused by livestock, our results indicate that livestock exert a lower browsing pressure than wild ungulates at current grazing conditions, as hypothesized. Livestock are usually characterized as 'grazers', since they tend to avoid the consumption of woody plants except in situations with very high stocking densities or fodder scarcity (Mayer, 2006; Vandenberghe, 2007). The high overall herb availability in the study area during summer may thus have contributed to the moderate browsing pressure observed for livestock. On the other hand, wild ungulates are more selective and cause more abundant and severe damages than cattle to seedlings, often being described as 'browsers' (Didion et al., 2009; Liss, 1988; Mayer, 2005b, 2006). The browsing behavior is particularly important during winter, when other food resources are scarce and seedlings constitute a significant part of their diet (Häsler and Senn, 2012; Jackson, 2009; Motta, 1996).)" (Ameztegui and Coll 2015) "For the three conifer species, browsing-induced mortality rates observed in the study area were low or moderate, as they never exceeded 15%. The low browsing pressure observed on both pines matches previous studies that suggest a low palatability of these species (Didion et al., 2011). In contrast, fir is considered one of the preferred species by ungulates, which cause significant difficulties for its regeneration in mountain areas of Central Europe (Ammer, 1996; Heuze et al., 2005; Motta, 1996; Senn and Suter, 2003). In this study, we unexpectedly found low browsing rates on fir seedlings, but this could probably be explained by the small size reached by the plants four years after planting. For *A. alba*, *P. sylvestris* and *P. uncinata*, browsing induced similar or lower mortality than that observed for other causes, such as lack of climatic adaptation or sensitivity to extreme climatic events (Ameztegui and Coll, 2013). Therefore, one might conclude that browsing does not play a decisive role in the dynamics of these species, or at least not to the point of limiting or preventing their regeneration. For birch, which concentrated most of the damage by browsing, herbivory could be more limiting, especially considering the pioneer nature of this species, which normally regenerates abundantly in forest gaps after disturbances." (Ameztegui and Coll 2015) Overall, we identified the cause of mortality for 95.9% of the seedlings, the main cause being summer drought (51.8%; Fig. 2), followed by pathogens (22.6%), hailstorms (13.9%) and herbivory (9.6%), with significant differences among causes ($c2 = 133.04$; $df = 3$; $p < 0.0001$; minor causes such as vole tunnels and frost heave were not considered in the analysis). (Castro et al.2002)

Species	Common	Seedling survival
		"Only five seedlings emerged in the uncaged plots (Table 2), which were omitted from further analysis; we found remains of seeds depredated by rodents and birds (separated seed coats or bitten seeds) in all plots. For the caged plots, significant differences appeared among treatments for seedling emergence ($F = 35.68$; $df = 2$; 52 $p < 0.0001$; one-way ANOVA). The highest value was recorded in the Disturbed treatment (55.5%), where the seeds were in direct contact with the mineral soil (Table 2). In Control and Clipped treatments many seeds had germinated and expanded the radicle over the ground for some days, but the majority desiccated and died before rooting" (Castro et al.2002) "The results show that the probability of Pinus sylvestris seedling emergence in the meadows is extremely low under natural conditions. Values were below 1% in all treatments for surface-sown seeds (simulating natural dispersal), despite the fact that the seed rain assigned mimicked a mast year (Koski 1991). These low values can be explained in two ways. First, post-dispersal seed predators consumed most of the surface-sown seeds and consequently the emergence of seedlings was almost nil in uncaged plots. This implies that predation was a main factor constraining the encroachment of *Pinus*, which is in agreement with previous studies showing that rodents and birds consumed most of the dispersed *Pinus* seeds in the forests (Castro et al. 1999). Second, the herbaceous layer hampered seedling emergence for seeds protected against predators, decreasing emergence from 55.5% on exposed soil to 6.4% with an intact herbaceous layer. The effect of the herbaceous layer, however, vanished when seeds were sown 1 cm deep; in that case emergence values were similar for all treatments. This, together with the pattern of emergence for surface-sown seeds, strongly suggests that the herbaceous layer constitutes a physical barrier against recruitment, which may result from two non-exclusive processes related to seed-soil contact. First, seed germination in the surface of the herbaceous layer may be hampered because hydraulic conductivity is lower than in the mineral soil (Hadas 1982). In fact, under non-saturated conditions (which prevail in Mediterranean mountain meadows), a layer of organic matter hampers the germination of *Pinus* seeds compared with rates on a mineral soil, whereas a slight burial that improves seed-soil contact increases the germination rate (Oleskog et al. 2000; see also Dolling 1996). Second, once a seed has germinated, the herbaceous layer may also block the radicle from reaching the mineral soil, resulting in seedling death by drying or depletion of reserves before reaching water and nutrients from the soil (e.g. Borchert et al. 1989). Many seeds that germinated in the Control and Clipped treatments in the surface-sown experiment expanded their radicle through the surface but died after a few days and before rooting, indicating that they were suspended too far above the soil. The formation of such a physical barrier, which is created by growing plants plus decomposed litter, might be particularly relevant for grassy areas located in environments characterized by a dry growing season and low winter temperatures. This decreases the rate of litter decomposition (Gallardo 2001), reinforcing the formation of a carpet of herbaceous vegetation and dry litter that hampers seed imbibition and seed-soil contact (Xiong and Nilsson 1999). The results indicate, therefore, that the contact of the seed with the mineral soil is a critical requirement for the establishment of *Pinus sylvestris* on Mediterranean mountain meadows (cf. Magee and Antos 1992; Prach et al. 1996)" (Castro et al.2002) "While a high proportion of the seeds which were not eaten germinated and emerged as seedlings on the irrigated subplots at the forest edge (60–80 %), only 20–35 % of the seeds which were not consumed by seed

Species	Common	Seedling survival
		predators led to the emergence of seedlings on the open steppe and in the non-irrigated subplots at the forest edge (Fig. 4b). The rate of emerged seedlings increased with the mean soil water content, but decreased with the mean maximum temperature of the soil in the sample plots during the part of the growing season when seedling emergence was studied (Fig. 5)." (Dulamsuren et al.2013) "Seedling emergence increased with vegetation removal in the *Salix* shrubland (χ^2 = 33.65, p < 0.001, Table 2, Figure 3) and in the heath and meadow when vegetation removal was combined with willow introduction (interaction removal × transplant: χ^2 = 7.16, p = 0.007, χ^2 = 8.34, p = 0.004, respectively). Seedling survival also increased with vegetation removal combined with willow introduction (interaction removal × transplant: χ^2 = 10.27, p = 0.001), irrespective of community. In vegetation-removed subplots 6.4 times more seedlings survived than in subplots with vegetation intact. Patterns of seedling performance differed from those observed for seedling emergence and survival, and depended on the performance variable measured. The pines had greater fractions of healthy needles in vegetation-removed subplots than in intact subplots on the heath (F = 10.26, p = 0.001; Table 2, Figure 3) and in the *Salix* shrubland when vegetation removal was combined with willow introduction (interaction removal × transplant: F = 5.88, p = 0.015). In contrast, pines grew taller in intact subplots at the heath community (F = 10.99, p = 0.002; Table 2, Figure 3) and at the *Salix* shrubland site especially when vegetation removal was combined with herbivore exclusion (interaction removal × exclosure: F = 7.80, p = 0.007). New stem growth was not affected by the treatments." (Marsman et al.2021) Pine emergence increased when herbivores were excluded in the meadow (χ^2 = 8.66, p = 0.003; Table 2, Figure 3) and in the Salix shrubland when herbivore exclusion was combined with willow introduction (interaction exclusion × transplant: χ^2 = 3.92, p = 0.048). Pine seedling survival increased when protected from herbivores (χ^2 = 15.76, p < 0.001) for all communities. The effect of herbivore exclusion on stem height was inconsistent among sites (Appendix S3; Table S3.1, Figure 3). /in the shrubland and heath, the effect depended on complex interactions with vegetation removal and willow introduction, respectively, while we detected no effect at the meadow. When herbivores were excluded, pine seedlings had greater fractions of healthy needles on the heath and *Salix* shrubland (χ^2 = 4.17, p = 0.041, χ^2 = 6.63, p = 0.010, respectively; Table 2, Figure 3), but not in the meadow." (Marsman et al.2021) "None of the microclimatic variables detectably affected pine emergence. Seedling survival tended to increase with warmer maximum summer temperature, minimum winter temperature and light availability, although the estimated effects were weak (Table 3, Figure 5). Seedlings in plots characterized by high maximum summer temperatures, moister soils and higher light availability had greater fractions of healthy needles. Furthermore, seedlings grew taller in plots where less light was available. All of the estimated effects were weak." (Marsman et al.2021)
Pinus mugo complex	mountain	"By mid-December, approximately 60% of the seed sown had become established as seedlings. (Ledgard 1977) "Major first year seed and seedling losses resulting from the direct sowing of pine seed on an exposed subsoil at 850 m altitude were attributed to birds (100% unprotected plots), failure of emerging radicle to penetrate the subsoil (15%), insect attack (15%), and frost heave (44%). Losses of lesser significance were caused by mice." (Ledgard 1977)

Species	Common	Seedling survival
		"Open plots within a day of sowing, 10% of the seed had disappeared…after 7 days only 2 seeds of the original 500 sown could be located" (Ledgard 1977) *Pinus uncinata* Browse-induced mortality: (montane) 0.09; (subalpine) 0.07 lack of adaptation (montane) 0.15; (subalpine) 0.13 other (montane) 0.02; (subalpine) 0.20 (Ameztegui and Coll 2015) Montane belt (% Browsed seedlings, % Lethality); Subalpine belt (% Browsed seedlings, % Lethality); Average (% Browsed seedlings, % Lethality) *Abies alba* 12.5, 77.8; 23.6, 70.6; 18.1, 73.1 *Betula pendula* 65.0, 55.6; 63.9, 56.5; 69.4, 56.0 *Pinus sylvestris* 11.1, 62.5; 18.1, 69.2; 14.5, 66.7 *Pinus uncinata* 9.8, 85.7; 12.5, 77.8; 11.1, 81.2 (Ameztegui and Coll 2015) "At the microhabitat level we found, as expected, the browsing-induced mortality of *P. uncinata* and *A. alba* to decrease when seedlings were growing close to a shrub. The role of shrubs as facilitators of tree regeneration has been widely observed in mountain areas, where shrubs act as 'biotic refuges' for seedlings (Heuze et al., 2005; Milchunas, 2002; Vandenberghe, 2007). In Mediterranean mountains, habitat amelioration has been pointed out as the main mechanism behind this facilitative effect (Castro et al., 2004; Gómez-Aparicio and Canham, 2008). This was also observed in a previous work conducted in the same area, in which we found a protective role of shrubs on seedlings face to adverse climatic events (Ameztegui and Coll, 2013). The results of the present study indicate that, in addition to habitat amelioration, shrubs also increase plant survival by providing physical protection from herbivores, denoting that both mechanisms co-occur in Mediterranean mountain systems (as also found by Boulant et al., 2008)." (Ameztegui and Coll 2015) "Browse-induced mortality rate during winter (i.e. caused exclusively by ungulates) was similar to browse-induced mortality observed during summer, when plots can be frequented by both wild ungulates and domestic livestock. However, intra-guild competition was probably occurring in the study area during summer, when the presence of cattle forced the ungulates to take refuge in the rocky slopes located above the main grazing areas. Thus, assuming that most of the summer browsing-induced mortality is caused by livestock, our results indicate that livestock exert a lower browsing pressure than wild ungulates at current grazing conditions, as hypothesized. Livestock are usually characterized as 'grazers', since they tend to avoid the consumption of woody plants except in situations with very high stocking densities or fodder scarcity (Mayer, 2006; Vandenberghe, 2007). The high overall herb availability in the study area during summer may thus have contributed to the moderate browsing pressure observed for livestock. On the other hand, wild ungulates are more selective and cause more abundant and severe damages than cattle to seedlings, often being described as 'browsers' (Didion et al., 2009; Liss, 1988; Mayer, 2005b, 2006). The browsing behavior is particularly important during winter, when other food resources are scarce and seedlings constitute a significant part of their diet (Häsler and Senn, 2012; Jackson, 2009; Motta, 1996)." (Ameztegui and Coll 2015)

Species	Common	Seedling survival
		"For the three conifer species, browsing-induced mortality rates observed in the study area were low or moderate, as they never exceeded 15%. The low browsing pressure observed on both pines matches previous studies that suggest a low palatability of these species (Didion et al., 2011). In contrast, fir is considered one of the preferred species by ungulates, which cause significant difficulties for its regeneration in mountain areas of Central Europe (Ammer, 1996; Heuze et al., 2005; Motta, 1996; Senn and Suter, 2003). In this study we unexpectedly found low browsing rates on fir seedlings, but this could probably be explained by the small size reached by the plants four years after planting. For *A. alba*, *P. sylvestris* and *P. uncinata*, browsing induced similar or lower mortality than that observed for other causes, such as lack of climatic adaptation or sensitivity to extreme climatic events (Ameztegui and Coll, 2013). Therefore, one might conclude that browsing does not play a decisive role in the dynamics of these species, or at least not to the point of limiting or preventing their regeneration. For birch, which concentrated most of the damage by browsing, herbivory could be more limiting, especially considering the pioneer nature of this species, which normally regenerates abundantly in forest gaps after disturbances." (Ameztegui and Coll 2015) "Seed source and viability were not critical factors for seedling establishment. Far more important was the presence of suitable bare-surface microhabitats with thin or no organic layer near mature pine stands. Vegetation communities dominated by *Avenella flexuosa* and *Nardus stricta* facilitated seedling establishment; communities dominated by Vaccinium myrtillus showed strong competitive effects on seedlings. Vegetation's effect on seedling establishment was closely related to disturbance regime, which influences vegetation type. Seedling mortality was highest in the first year of life irrespective of microsite vegetation type. Highest mortality was associated with open mineral-soil microsites, while microsites with dense herbaceous vegetation showed the lowest. Conclusions: Potential *Pinus mugo* expansion will occur in close proximity to existing mature stands, and its intensity will be strongly modified by site-specific density of suitable microsites and/or dominant species of host communities." (Šenfeldr and Treml 2020) "We collected data on: (a) seed quantity and quality; (b) seedling microsite preferences; and (c) seedling survival during initial ontogenetic stages. From 2006 to 2016 we assessed cone production annually and tested seed viability every second year. Microsite preferences were analyzed for 650 seedlings at six sites. The following microsite characteristics were recorded for 1-m^2 around each seedling: percentage of bare surface; surrounding plant species cover; surface shape; and organic horizon thickness. Additionally, distance and direction to the nearest adult pine were recorded. Finally, we tested survival of 200 newly established seedlings in relation to microsite type. Results: Seed source and viability were not critical factors for seedling establishment. Far more important was the presence of suitable bare-surface microhabitats with thin or no organic layer near mature pine stands. Vegetation communities dominated by *Avenella flexuosa* and *Nardus stricta* facilitated seedling establishment; communities dominated by *Vaccinium myrtillus* showed strong competitive effects on seedlings. Vegetation's effect on seedling establishment was closely related to disturbance regime, which influences vegetation type. Seedling mortality was highest in the first year of life irrespective of microsite vegetation type. Highest mortality was associated with open mineral-soil microsites, while microsites with dense herbaceous vegetation showed the lowest. Conclusions: Potential *Pinus mugo* expansion will occur in close proximity to existing mature stands, and its intensity will be strongly modified by

Species	Common	Seedling survival
		site-specific density of suitable microsites and/or dominant species of host communities." (Šenfeldr and Treml 2020)
Pinus nigra	black, Austrian	"Newly germinated seedlings suffered very heavy losses from voles and rabbits but became unpalatable to them within 2 months." (Burns and Honkala 1990) "European black pine is susceptible to infection by many pathogens that damage seedlings, foliage, stems, and roots." (Burns and Honkala 1990) "The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) < European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) < Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993)." (Ledgard 2001) "Ungrazed grassland environments were most vulnerable to invasion and the highest elasticities and sensitivities of invasion speed were to long-distance dispersal parameters." (Buckley et al.2005) "In shrubland invasion speed was most sensitive to the probability of establishment, especially when establishment was low. In the grazed environment elasticity and sensitivity of invasion speed to the severity of grazing were consistently highest. Management recommendations based on elasticities and sensitivities depend on the vulnerability of the habitat." (Buckley et al.2005) Once emerged, seedlings protected by wire cages had significantly longer survival rates, consistent with our expectations and indicating the important role of herbivores in killing young trees." (Lucas-Broja et al.2017) "Post-dispersal seed predation is known to have severe recruitment consequences, acting as a strong impediment to the natural regeneration process in many forest species (Hulme, 1998; Vander Wall et al., 2005). In relation to other species and Spanish black pine origins, Pardos et al. (2005) reported that predation of *Quercus ilex* acorns can affect up to 50% of the annual crop. For Spanish Black pine located in the Pyrenees (*Pinus nigra* Arn ssp. *salzmannii* var. *pyrenaica*), Ordóñez et al. (2004) found that predators consumed between 33% and 18% in burned and unburned plots, respectively." (Lucas-Broja et al.2017) Studied, species: *P. nigra*, *P. pinaster*, *P. halepensis*, Germination rate: 76 ± 23, 35 ± 26, 26 ± 23, Survival rate: 6 ± 10, 11 ± 20, 12 ± 18, Treatment (Control, Fire, Scalping) Germination rate, 39 ± 31, 35 ± 37, 62 ± 21 Survival, rate, 11 ± 20, 2 ± 7, 13 ± 17, Seed protection (Yes, No) Germination rate, 47 ± 30, 43 ± 35,

Species	Common	Seedling survival
		Survival, rate, 14 ± 19, 3 ± 11 (Lucas-Borja et al.2018a) "According to our results, Spanish black pine displayed the best germination performance with 76% of seeds, whereas Aleppo pine obtained the lowest rate (26%). We obtained a higher seedling survival rate for Aleppo pine (12%), followed by Maritime pine and Spanish black pine (seedling survival rates of 11% and 6%, respectively). The treatment that most favoured both emergence and survival was scalping with 62% germination and 13% survival, while the least helpful one was prescribed fire with 35% germination and only 2% survival. For protection from predators, when taking into account all seeds, similar values in germination for this factor were obtained. Finally, survival indicated higher predation outside protection (11% higher in the unprotected plots than in the protected ones)." (Lucas-Borja et al.2018a) "We sampled *Pinus nigra* cones in 29 trees in an age range of 90 to 725 years. The mother tree age did not significantly influence the pinecone or pine seed size, seed germination capacity, or plant size or vigor displayed during the first year of growth in the nursery" (Alejano et al.2019) "Throughout the growing season, seedling survival was greater for seedlings grown from control populations than for those grown from rocky populations, with the exception of those from the Višegrad provenance (Fig. 3). In the early measurement dates, seedling survival did not differ among the stressbed treatments. However, by mid-May and through the end of the study differences in survival were evident (Table 5). Average survival rate for all open-pollinated families in stressbed-3 was 63 % which was 15 and 18 % higher than seedling survival in stressbed-2 and stressbed-1, respectively" (Mataruga et al.2012) "In all provenances (except Višegrad) seedlings propagated from parent trees growing in the most favorable habitats (control populations) had higher survival rates regardless of water availability. These survival patterns were similar to seed germination patterns from the same populations (Mataruga et al. 2010). In contrast, a study with Maritime pine (*Pinus pinaster* Aiton) seedlings from seed sources originating from hotter sites demonstrated a larger and more rapid acclimation to water stress conditions than those from cooler sites (Fernández et al. 1999). Zhang et al. (1997) found that ponderosa pine seedlings (*Pinus ponderosa* Dougl. Ex Laws.) from a highly drought-tolerant population were more sensitive to water availability than seedlings from other populations; they used water quickly when water was available, but closed their stomata in response to water stress. They concluded that the drought avoidance mechanism in ponderosa pine is more important for survival and growth in arid environments than water-use efficiency." (Mataruga et al.2012) "Mean seedling survival at the final assessment did not differ significantly between the two species (Douglas fir 36 ± 3.8%, Corsican pine 28 ± 3.0%), but there were highly significant ($P < 0.01$) interactions between species and site, and species and vegetation cover. Survival of Douglas fir seedlings was greater than for Corsican pine at Bealey, Cass and Okuti sites while survival of Corsican pine was greater at Eyrewell. Survival of the two species was similar at Ellangowan and Avoca (data not presented). Survival of Corsican pine seedlings was greatest in the open and declined progressively as canopy cover increased. This contrasted with Douglas fir where seedling survival was greatest at the edge position (Fig. 3). Seedling survival of Corsican pine was greater than for Douglas fir at the open position, whereas survival of Douglas fir seedlings was greater at the

Species	Common	Seedling survival
		edge, moderate- and dense-canopy positions, though the difference was significant only at the dense-canopy position (Fig. 3)" (Davis et al.2011) "Fertilizer Treatment and removal of competition: Where fertiliser had been used in combination with the "slot-wing" and "Baker Boot" coulters at Mt Barker, *P. nigra* seedlings were inundated by the resident vegetation during the first growing season. No measurements could be made for these treatments. Seedling survival rate in plots without fertiliser was not significantly affected by competition removal (Fig. 2a). Seedling height was decreased slightly but significantly by competition removal in the first season; however, this difference was reduced over the following year because of slightly greater growth where competition was removed (Fig 2b). Within the "strip" coulter treatment, fertiliser application clearly depressed survival rate (Fig 3 a), but had no effect on seedling height (Fig 3b)." (Davis et al.1996)
Pinus ponderosa	Ponderosa	"In Oregon and Washington, higher survival and growth rates of ponderosa pine have been reported for coarse-textured sandy soils than for fine-textured clayey soils." (Burns and Honkala 1990) "The significance of competing vegetation as a deterrent to early survival and development of young seedlings has been clearly demonstrated. In central Idaho, soil moisture remained above the wilting point at depths below 15 cm (6 in> on areas free of competing vegetation throughout the growing season but dropped to or below that critical point on most vegetated plots (13). In loamy soils in the White Mountains in Arizona, drought is normally not a major variable in seedling survival beyond age 2, except where there is grass cover. Shrub competition reduced the height and diameter growth of ponderosa pine planted in northern California; similar growth reductions have been reported for stands in Oregon." (Burns and Honkala 1990) "At least 108 species of insects attack *P. ponderosa* var. *ponderosa*, and 59 species attack *P. ponderosa* var. *scopulorum*." (Burns and Honkala 1990) "The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) < European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) < Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993)." (Ledgard 2001) "EMF root colonization decreased with distance from plantation (p = 0.0139, Fig. 2, Table 4). Mean EMF root colonization at the pine plantation edge was ca. 90% while it decreased to ca. 40% at the furthest distance from the plantation evaluated here (200 m). However, we found no differences in seedling growth (shoot height and biomass) or survival with distance from plantation (pheight = 0.6387; pbiomass = 0.9911; psurvival = 0.4830). When we pooled all distance levels together and compared seedlings colonized by EMF (ranging from 10% to 100% EMF root colonization) with seedlings un-colonized (0% EMF root colonization) we found differences in seedling biomass favoring colonized seedlings (p = 0.0400, Suppl. material 1: Fig. S1). " (Moyano et al.2019b) "Here, we investigated seed predation by deer mice (*Peromyscus maniculatus*) and its effects on recruitment of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) seedlings in unburned and recently burned fire-adapted montane forests in west-central Montana, USA. Deer mice were almost twice as

Species	Common	Seedling survival
		abundant in burned than unburned stands. Deer mouse removal of seeds from petri dishes was two times higher in burned than in unburned stands, and seed removal levels were 8% higher for ponderosa pine than for the smaller Douglas-fir seeds. In seed-addition experiments, emergence of seedlings in deer mouse-exclusion cages was almost six times higher in burned compared to unburned forest. In both burned and unburned forest, emergence was lower for ponderosa pine than for Douglas-fir. Seedling survival to establishment did not differ between conifer species but was considerably higher in burned than in unburned forest. However, effects of seed predation on recruitment prevailed over fire effects: in cages allowing access by deer mice, emergence and establishment were extremely rare for both conifer species in both burned and unburned forest. This research suggests that consumer interactions can substantially influence recruitment even in fire-adapted forest ecosystems." (Zwolak et al.2010) "Estimated abundance of deer mice was 1.6 times higher in burned compared to unburned forest in 2006 (22.6 6 0.9 vs. 14.3 6 0.5 mice/grid, mean 6 SE), and 1.8 times higher in burned compared to unburned forest in 2007 (54.2 6 2.8 vs. 29.5 6 2.7 mice/grid; Table 1)." (Zwolak et al.2010) "Seed removal at night was higher in burned vs. unburned forest, particularly in 2006 (fire and fire 3-year effects; Table 2a, Fig. 1a). In addition, more ponderosa pine than Douglas-fir seeds were removed at night (species effect; Table 2a, Fig. 1a). During the day, overall differences in removal between burned and unburned forest were not significant. However, in contrast to nighttime removal, daytime removal was less intense in burned vs. unburned forest in 2007 (fire 3-year effect; Table 2b, Fig. 1b). As in nighttime trials, removal was greater for ponderosa pine seeds compared to Douglas-fir seeds, though this was only significant in 2007 (species 3-year effect; Table 2b, Fig. 1b)." (Zwolak et al.2010) "Seedling emergence in cages without rodent access was considerably higher in burned vs. unburned stands (fire effect; Table 3), but this effect disappeared in cages with rodent access (rodent access 3 fire effect; Table 3). In cages without rodent access, 39% of seedlings emerged in burned forest vs. 7% in unburned forest, while in cages with access, 0% of seedlings emerged in burned forest vs. 0.9% in unburned forest (Fig. 2a). Overall, seedling emergence was lower for ponderosa pine compared to Douglas-fir (species effect; Table 3). The difference between conifer species was not affected by fire or by mice (fire 3 species and rodent access 3 species interactions were nonsignificant and eliminated from the final model). Seedling survival also differed strongly between burned and unburned forest ($z = 2.72$, $P < 0.006$; Fig. 2b). In 2007, 75% (55 out of 73) of seedlings in burned forest survived until September, whereas survival observed in unburned forest was only 30% (eight out of 27 seedlings survived). In 2008, the overall pattern of higher survival in burned forest remained unchanged, but survival in both burned (30%, 23 out of 76 seedlings) and unburned (0 out of 10 seedlings) forest was lower than in 2007 ($z = -5.48$, $P < 0.0001$). Besides fire and year, no other factors were significant predictors of seedling survival." (Zwolak et al.2010) "In 2007, the proportion of seeds sown that reached the establishment stage when mice were excluded was ~26% for ponderosa pine and 34% for Douglas-fir in burned stands, compared to 1% and 4%, respectively, in unburned stands; mouse access reduced these values to 0% in burned stands and <1% in unburned forest. In 2008, establishment without mice was ~1% for ponderosa pine and 16% for Douglas-fir in burned stands,

Species	Common	Seedling survival
		compared to <1% for both species in unburned stands; mouse access reduced these proportions to 0." (Zwolak et al.2010) "Survival of transplanted seedlings at the end of the experiment in September 2004 was 28.7% for seedlings planted in 2002 (cohort 1) and 30.2% for seedlings planted in 2003 (cohort 2). For both cohorts, seedling survival during the first year was higher on sandy soils and lower on fine-textured soils (Table 1), but showed no relationship to thermal factors. During the second year, cohort 1 survival was not related to soil texture or herb cover, but showed a significant decrease with lower minimum temperatures (Table 1). Cohort 1 survival in 2003 was also lower where herbs were present, although the effect was only about half as strong as that for percentage sand (Table 1). We also found a significant positive effect of herbs 3 sand for cohort 1 survival in 2003, as expected if competition is more intense on finetextured soils. We attributed seedling mortality to three causes. The first of these, physiological stress (seedlings exhibited poor growth, a gradual browning and dropping of needles, and no apparent physical damage by insects or mammal herbivores), killed 37.7% of transplanted seedlings. The second source of mortality, rodent activity, was due primarily to aboveground damage by golden-mantled ground squirrels (*Spermophilus lateralis*), although we also noted cases in which seedlings had been uprooted, tunneled beneath, or buried by pocket gophers (*Thomomys* spp.). Rodents killed 29.7% of transplanted seedlings. Lastly, 2.9% of our seedlings died from other causes, including trampling by ungulates, defoliation by grasshoppers, and factors unknown. Total mortality caused by rodents or physiological stress was roughly equal across silty and sandy soils (Fig. 1). On cold sites, however, mortality was primarily caused by stress, whereas on warm sites it was caused mainly by rodents (Fig. 1)." (Coop and Givnish 2008) "We found the strongest support for our first hypothesis: low minimum temperature, associated with nocturnal cold-air accumulation, limits tree seedling establishment below reversed tree lines in the VCNP (Figs. 2 and 3, Table 2). At sites experiencing lower nocturnal temperatures in the valley bottoms, seedlings exhibited greatly decreased height and needle growth. Although we found evidence for low-temperature photoinhibition in the relationships of fluorescence ratios to minimum temperature (Table 3), photoinhibition does not appear to wholly account for the relationship of growth to temperature, given the strong ties of fluorescence ratios to percentage sand and soil moisture, which were themselves not strong predictors of seedling growth. These findings suggest that growth was limited directly by freezing damage, beyond the energetic costs imposed by photoinhibition. Growing conifer needles may be particularly susceptible to frost damage; Schubert and Adams (1971) reported that temperatures lower than 38°C injured unhardened ponderosa pine needles, and temperatures during the growing season dropped below this threshold in the valley bottoms of the VCNP. Needles at experimental sites experiencing low temperatures were stunted and often appeared physically damaged (for photos, see Appendices). The compounding effects of decreased needle growth should limit subsequent energy capture and plant growth, and should increase vulnerability to other sources of mortality, and we found that needle growth was the single best predictor of both height growth and seedling survival in the following year. One likely consequence of damaged needles is increased winter desiccation; Tranquillini (1987) found that Norway spruce (*Picea abies*) needles required at least 50 consecutive days without frosts of -38°C to avoid damage during growth, but at least 90 days above -38C to develop needle cuticles adequate to resist winter desiccation. The strong effects of frequent frosts in valley bottoms that we observed on the growth

Species	Common	Seedling survival
		of 1–3-year-old seedlings are likely to be equally or even more detrimental to seedlings between 0 and 1 years old, and could preclude any conifer establishment at the coldest sites." (Coop and Givnish 2008) "We found less support for our hypotheses that edaphic factors and herb competition impede seedling growth or survival. Percentage sand was a significant predictor of first-year transplanted seedling mortality, although the magnitude of this effect was substantially less than that of temperature on seedling growth (see Tables 1 and 2, Fig. 2). Both percentage sand and soil moisture were positively associated with photosynthetic performance (Table 3), suggesting physiological stress imposed by low soil moisture potentials; however, these factors were not related to seedling growth. Although we found support for edaphic controls on herbaceous plant cover and biomass, we found less support for any subsequent effect on ponderosa pine establishment (i.e., the herb 3 sand interaction term, significant in only one model), beyond a minor negative effect of competition occurring across all sites (the herb term alone, significant in several models of survival, growth, and photosynthetic performance; Tables 1–3). Taken together, these findings suggest some physiological stress imposed by low moisture potentials on fine-textured soil, possibly exacerbated by grass competition. Although these conditions exerted only minor effects on our transplanted seedlings, we cannot exclude the possibility that they decrease germination and/or seedling survival soon after germination." (Coop and Givnish 2008) "Survival of naturally germinating pine seedlings in this study followed a consistent pattern, regardless of the year of germination. Only a small portion of naturally germinating seedlings survived for more than a few years, with most mortality occurred during the first 2 years after germination (Figure 7). Overstory and site preparation treatments strongly influenced survival of seedlings that originated in 1982, 1989, and 1995, but not other years. Generally, more seedlings survived under shelterwood overstories and on scarified seedbeds for the above 3 years (Table 1). These data suggest that denser overstories and scarified seedbeds help promote seedling survival in years with abundant seed germination. However, confounding effects of the treatments from year to year negated the overall effects of overstory and site preparation treatments on natural seedling survival in this study (Table 1)." (Shepperd et al.2006) "Seedling survival in experiment B [distributed watering] was considerably greater that experiment A [once / month] at the higher watering levels. Less than 20% of the seed sown survived at the three highest water levels in experiment A while 42% 66% and 87% of the seeds sown survived in experiment B." (Shepperd et al.1976) "1955-60. From start of seed fall until the end of germination in late spring following year, 12% of the Douglas-fir (*Pseudotsuga menziesii*) seed survived. Ground-feeding birds and small mammals caused 63% of the seed loss and other agents 25%. Thirty-one per cent of the seed of western hemlock (*Tsuga heterophylla*) lived from the start of seed fall until the end of germination. Of the amount lost, birds and mammals took 16% and all other factors 53%. A large proportion (65%) of western redcedar (*Thuja plicata*) seed survived during the same period. The entire loss was attributed to causes such as nonviable filled seeds, disease, invertebrates, and others. Ground-feeding birds and small mammals showed a definite preference for Douglas-fir seeds. Only about 25% as many hemlock seeds were taken, and redcedar was not consumed in appreciable amounts.

Species	Common	Seedling survival
		Most of the seed depredations by birds and mammals occurred from start of seed fall to start of germination; other factors took heaviest toll during the germination period.]" "In this study, 99% of the mortality was attributed to three causes -- drought, failure to establish, and damping off. Drought was the primary cause of mortality at all watering levels in experiment A and in all but the 2.0 in treatment in experiment B." (Shepperd et al.1976) survival on induced erosion pavement after five years: 22 of 100 (Wendelken 1963) survival (3-6 years) in depleted forest depended on vegetation cover: stable bare soil > unstable bare soil > grass/herbs = mat pants = litter (Wendelken 1963) 1-year-old seedlings per acre when opening size was 30 feet; 60 feet; 90 feet: 112; 162; 288 (McDonald 1966) "We found the strongest support for our first hypothesis: low minimum temperature, associated with nocturnal cold-air accumulation, limits tree seedling establishment below reversed tree lines in the VCNP (Figs. 2 and 3, Table 2). At sites experiencing lower nocturnal temperatures in the valley bottoms, seedlings exhibited greatly decreased height and needle growth...the compounding effects of decreased needle growth should limit subsequent energy capture and plant growth, and should increase vulnerability to their sources of mortality, and we found that needle growth was the single best predictor of both height growth and seedling survival in the following year. One likely consequence of damaged needles is increased winter desiccation" (Coop and Givnish 2008)
Pinus muricata	bishop	The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) <European larch (*Larix decidua*) <Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) < Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993). (Ledgard 2001)
Pinus pinaster	maritime	"Seedling establishment and survival processes in *P. pinaster* are closely related to seed germination, thus more favorable sites for germination are those more favorable for survival. However, initial seedling survival is largely threatened by water stress during the summer (Fig. 5), as well as interactions with other factors. In particular, mid-shaded conditions, the presence of shrubs acting as nurse plants (Rodríguez-García et al., 2011) and needle soil cover (del Peso et al., 2012) facilitate *P. pinaster* germination, emergence and initial survival." (Calama et al.2017) "In Stand 1, the average fecundity was 2.56 recruits/adult (268 adults and 686 recruits). In Stand 2, the average fecundity was slightly higher, 3.25 recruits/adult (44 adults and 143 recruits)." (Charco et al.2017) "Cone production by adult trees does not seem to be a limiting factor to regeneration and expansion of this population given that 268 trees in Stand 1 and 44 in Stand 2 are seen with cones in their crowns. Furthermore, some of them (the most vigorous) may be classified as high seed producers having up to 587 and 193 cones in Stand 1 and 2, respectively, while some really short individuals (just 0.5 m height) are seen with cones in their small crowns. Nevertheless, the distribution in reproductive success (in the seed stage) that was shown to be unequal among adults (25% of adults have less than 5 visible cones on their crown in Stand 1) should be a factor that reduces the regeneration potential of this stand. On the other hand, fecundity is dramatically

Species	Common	Seedling survival
		reduced in both stands. Recruitment in this population started to be effective only after 1973 (the maximum age in the sample of recruits was 31 years when sampling was performed in 2004). This time period coincides with the ceasing of extensive livestock management and the disappearance of the associated activities, such as frequent pasture burning. However, the average number of recruits/adult (3.25 recruits/adult in Stand 2) is a clear indication of low recruitment potential. Several factors may be responsible; among others is the high density of deer living in the area, which by browsing and fraying can cause severe damage and mortality to the regeneration cohort [26]. Deer can also affect fecundity of mature pines since those trees highly damaged by fraying produce fewer cones [26]. In addition, severe summer drought effects in conjunction with the poor edaphic conditions (complete absence of soil in many areas due to erosion) may be important factors contributing to massive mortality during the seed-to-sapling transition. A recent study using seed from this population [23] showed that seedlings obtained from seeds of Stand 1 exhibited higher mortality rates in water-stress experiments as compared to seedlings grown from seeds from nearby plantations." (Charco et al.2017) "Cone bank and initial viable seed rain were highly correlated with initial seedling density (Fig. 2) whereas remaining duff load and depth negatively affected the initial pine establishment. Remaining duff load was the variable most negatively correlated with relative germination success. Duff load reduction and soil burn severity index were the variables most positively affecting the relative germination success." (Vega et al.2009) "Harvesting was the variable most negatively affecting the ratios final seedling density/initial density and final seedling density/ total viable seed rain. Remaining duff load and depth seemed to negatively affect both ratios. On its turn, soil burn severity index and serotiny level exerted a positive influence on these variables (Fig. 3)" (Vega et al.2009) "Seedling survival depended on seedling height ($x2 = 1084.64$; $p < 0.001$) and the type of post-fire management ($X^2 = 54.66$; $p < 0.001$). Harvesting-caused mortality varied from 51% immediately after harvesting and slash chopping to 71% after harvesting + slash windrowing" (Vega et al.2009) Final seedling density/initial seedling density: high 1.40 (0.37); medium 0.92 (0.26); low 0.96 (90) (Vega et al.2009) Final seedling density/total viable seed rain: high 0.06 (0.02); medium 0.04 (0.01); low 0.03 (0.01) (Vega et al.2009) "In the case of Stand 1, the average density of *P. pinea* and *P. pinaster* seedlings over the study period was 2197 and 127 seedlings ha^{-1}, respectively, whereas in Stand 2 the average density of seedlings was 397 for *P. pinea* ha^{-1} and 11 seedlings for *P. pinaster* ha^{-1}." (Moreno-Fernández et al.2018) "Our results showed a greater likelihood of establishment for a provenance from a more arid and warmer climate than the study location, when comparing treatments and sites." (Sagra et al.2018) "Under favoured conditions, fire can promote *Pinus pinaster* germination (Calvo et al., 2008). However, our analysis showed higher germination, a longer mean germination time and better establishment success in three control areas. In fact, prescribed burning affected soil properties in the short term; i.e. soil moisture and soil respiration diminished while soil temperature increased (Plaza-Álvarez et al., 2017). These changes play an important role on the seed performance, mainly in the first weeks after seeding, when pine seed and

Species	Common	Seedling survival
		seedling requirements for emergence and survival are stricter (Gómez et al., 2004). These restrictions are also intensified by both the effect of burning and summer drought (Madrigal et al., 2004; Padilla and Pugnaire, 2007). Likewise, a negative response of *Pinus pinaster* seedlings to scrub removal by fire has been reported in another study (Rodríguez-García et al., 2011). The lowest values for the survival and germination rates were found in the Post seeding units, which agrees with those studies that have indicated that ash accumulates after fire as a restrictive factor for recruitment in pine species (Izhaki et al., 2000; Ne'eman et al., 1993; Vega et al., 2008). Reyes and Casal, 2004, have observed that the larger amount of ash, the more negative the effect on the germination of four pine species, including *Pinus pinaster*. In our case both the Pre and Post seeds and seedlings were exposed to ash. However, ash seemed to act as a limiting factor on seed germination and seedling survival, only on the individuals sown after fire (mimicking dispersion during fire). Therefore, serotinous provenances may be more negatively affected by ash compared to those disseminated before prescribed fire. Severe wildfires can increase nutrient availability and enhance seedling growth (Eugenio et al., 2006). However, low-severity wildfires may induce such an important increase in nutrients and water-extractable elements (Pereira et al., 2012)." (Sagra et al.2018) "Individuals in control plots of the three species showed similar germination and survival levels in both drier and wetter provenances. Nevertheless, in the burned plots, both pre-fire and post-fire, show significant differences between the germination and survival rates of the drier and wetter provenances. Survival and germination were higher in the drier than in the wetter provenance for the three variables (germ, survsumm and survtot) in *P. pinaster* and *P. nigra*." (Sagra et al.2019) "Regarding treatments, the control plots generally shows higher germination and survival levels for the three species than those plots at the burned sites when comparing within same provenance (Fig. 4). The Pre-fire individuals displayed higher germination and survival rates than the Post-fire ones comparing within same provenances, with the exception of *P. nigra* which does not show these higher results on seeds exposed to fire (Pre-fire)." (Sagra et al.2019) Once emerged, seedlings protected by wire cages had significantly longer survival rates, consistent with our expectations and indicating the important role of herbivores in killing young trees."(Lucas-Broja et al.2018b) Studied, species: *P. nigra*, *P. pinaster*, *P. halepensis*, Germination rate: 76 ± 23, 35 ± 26, 26 ± 23, Survival rate: 6 ± 10, 11 ± 20, 12 ± 18, Treatment (Control, Fire, Scalping) Germination rate, 39 ± 31, 35 ± 37, 62 ± 21 Survival, rate, 11 ± 20, 2 ± 7, 13 ± 17, Seed protection (Yes, No) Germination rate, 47 ± 30, 43 ± 35, Survival, rate, 14 ± 19, 3 ± 11 (Lucas-Borja et al.2018a)

Species	Common	Seedling survival
		"According to our results, Spanish black pine displayed the best germination performance with 76% of seeds, whereas Aleppo pine obtained the lowest rate (26%). We obtained a higher seedling survival rate for Aleppo pine (12%), followed by Maritime pine and Spanish black pine (seedling survival rates of 11% and 6%, respectively). The treatment that most favoured both emergence and survival was scalping with 62% germination and 13% survival, while the least helpful one was prescribed fire with 35% germination and only 2% survival. For protection from predators, when taking into account all seeds, similar values in germination for this factor were obtained. Finally, survival indicated higher predation outside protection (11% higher in the unprotected plots than in the protected ones)." (Lucas-Borja et al.2018a) "The observed seedling survival rates for maritime pine seedlings by each measurement interval are presented in Fig. 4. Survival in both gap sizes was higher than in Exterior and Control subplots during the entire study period (around a 80% except in autumn 2020). ...The treatment had a significant effect on seedling survival (Fig. 5). Multiple comparison tests applied to evaluate the effect of treatment found that expected survival in subplots located in exterior and control subplots was significantly lower than the survival in both gap sizes (p value: 0.0286). No significant difference in seedling survival was found between gap sizes or between control and exterior subplots. Average survival was estimated at 90% in the larger gaps, at 87% in smaller gaps, while in the other locations (exterior and control regeneration subplots), it was lower than 80% (79 and 75 percent, respectively)." (Frutos et al.2023) "Early survival of seedlings is the main bottleneck to natural regeneration in many Mediterranean pine forests, mainly due to limited water availability during the summer drought and high light irradiance (Calama et al., 2017)" (Frutos et al.2023) "Emergence was generally low, ~2.73%, irrespectively of population origin. Total number of emergences (both experimental sites combined) was 985 (2.46%) and 1,203 (3.01%) seedlings from Coca and Calderona origins, respectively. Early survival was also very low. Only 32 (3.25%) and 24 (1.99%) seedlings from Coca and Calderona origins, respectively, remained at the end of the experiment, all of them found in the milder Calderona site." (Vizcaíno-Palomar 2014) "Water availability is the major limiting factor for maritime pine recruitment [36]." (Vizcaíno-Palomar 2014) "Waitemate District. The main species found regenerated in bush and scrub areas were radiata pine and maritime pine (*Pinus pinaster*). Regeneration occurs in open gaps in active regrowth, on earthwork or erosion surfaces, on sites degraded by burning where sporadic grazing and burning have occurred or on areas formerly grassed but allowed to revert to fern and scrub. It is concluded that invasion by pines poses no threat to native bush areas." (Chavasse 1979)
Pinus radiata	Monterey	"The best seedbed is moist mineral soil free of competing vegetation. Numerous seedlings, however, are found where the seedbed consists of several inches of pine needles over mineral soil." (Burns and Honkala 1990) "Seedlings develop best in full sunlight. Soil disturbed by logging and fire is conducive to seedling establishment and rapid growth. Dense slash decreases seedling density, although light slash can improve the seedling “catch.”" (Burns and Honkala 1990)

Species	Common	Seedling survival
		"Furniss and Carolin (12) list 56 insects from 44 genera that feed on Monterey pine foliage, twigs, branches, and boles. Relatively few of these cause significant damage and only five can kill trees, especially those weakened by other agents. Four are bark beetles and one is a weevil; all are cambium feeders." (Burns and Honkala 1990) "The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) <European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) <Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993)." (Ledgard 2001) "The proportion of emerged seedlings differed among microhabitats ($p < 0.05$) with strong evidence of an interaction between elevation and microhabitat ($p < 0.05$; Table 4.1; Fig. 4.1). Emergence within each microhabitat was lowest at 600 m, with similar proportions among elevations ($p > 0.123$) with the exception of disturbed plots at 1100 m ($p = 0.020$) and tussocks at 900 m ($p = 0.015$). The proportion of emerged seedlings was lowest in disturbed plots (0.01 – 0.10) and highest in tussocks (0.12 – 0.39) among all three elevations. Emergence within disturbed microhabitats was positively associated with elevation, while emergence was highest within undisturbed plots at 1100 m, and within tussocks and shrubs at 900 m. The proportion of seedling establishment (survival post winter of 2020) differed among elevations and across microhabitats with evidence of elevation interacting with both microhabitat and taxon ($p < 0.05$, Table 4.1; Fig. 4.2). Establishment was greatest overall at 900 m (0.33), followed by 1100 (0.32) and 600 m (0.26). The proportion of seedling establishment within disturbed and undisturbed plots was highest at 600 m with significant reductions in undisturbed plots at higher elevations (≥ 0.54; $p \leq 0.006$; Fig. 4.2a). Establishment within tussocks was significantly higher at 900 m compared to 600 m ($p = 0.004$), while establishment within shrubs was positively associated with elevation ($p < 0.001$). The establishment of both *P. radiata* seed sources was similar among the three elevations ($p \geq 0.497$; Fig. 4.2b) in contrast to the establishment of *P. radiata* × *P. attenuata* seedlings which were positively associated with elevation ($p \leq 0.010$)." (Gibson 2022) "Seedling survival in the first year exceeded 93.0% among all elevations for both caged and uncaged *P. radiata* seedlings (Fig. 5.1a). In the second year, all seedlings survived with the exception of one caged *P. radiata* at 1100 m (Fig. 5.1c). The relative SBD growth was similar between caged and uncaged seedlings ($p > 0.05$; Table 5.1; Figure 5.2a) and among elevations ($p > 0.05$). In contrast, the relative height increase in the first year differed between caged and uncaged seedlings ($p < 0.05$; Table 5.1; Fig. 5.3a) and among elevations ($p < 0.05$), with moderate to strong evidence of an interaction between cage treatment and elevation ($p < 0.05$). The relative height increase of caged seedlings was 34% greater than uncaged seedlings at 600 m ($p < 0.001$) and similar among 900 and 1100 m ($p > 0.755$). Among elevations, the relative height increase at 600 m was 72 and 81% greater than uncaged and caged seedlings at 1100 m, respectively ($p \leq 0.033$), while height at 900 m was 64 and 62% greater than at 1100 m, respectively ($p \leq 0.098$). The relative height increase in the second year only differed among elevations ($p < 0.05$; Table 5.1; Fig. 5.3c). The height increase of seedlings at 600 m was 50 to 64% and 71% greater than at 900 and 1100 m, respectively ($p \leq 0.002$), while the height increase of uncaged P. radiata at 900 m was 43% greater than at 1100 m ($p = 0.010$). The presence

Species	Common	Seedling survival
		of frost damage on seedlings was similar between caged and uncaged (p = 0.581), among elevations (p = 0.229), and their interaction (p = 0.233). The proportion of seedlings with frost damage varied between 62-70% for caged and 65-82% for uncaged, with 67-72% among elevations"(Gibson 2022) "Survival of uncaged *P. radiata* seedlings ranged between 93.3 and 98.3%, while survival of uncaged *P. radiata* × *P. attenuata* seedlings was 100% (Fig. 5.1b). In the second year, all seedlings survived with the exception of one uncaged *P. radiata* × *P. attenuata* at 600 m (Fig. 5.1d). Herbivory is unlikely the cause of mortality for either taxon in either year as none of the dead seedlings showed signs of herbivory. The relative SBD growth differed between taxa (p < 0.05; Table 5.1; Figure 5.2b) with moderate evidence of an interaction between taxon and elevation (p < 0.05). SBD growth for *P. radiata* × *P. attenuata* seedlings was 36 to 47% greater than for *P. radiata* seedlings across all elevations (p < 0.001). Compared to those at 600 m, the relative SBD growth of *P. radiata* × *P. attenuata* seedlings decreased by 27% at 900 m (p = 0.424) and 43% at 1100 m (p = 0.072). For *P. radiata* seedlings, SBD " (Gibson 2022) "The incidence of herbivore damage on uncaged *P. radiata* and *P. radiata* × *P. attenuata* seedlings in the first year was similar between the two species (p = 0.537; Fig. 5.4a) yet differed among elevations (p = 0.038). Herbivore damage was found on 40 to 45% of seedlings at 600 m compared to 0 to 3% at 900 m (p = 0.049) and 10 to 12% at 1100 m (p = 0.201. Incidence was similar between 900 and 1100m (p = 0.437). In the second year, the incidence of herbivore damage was similar between taxa (p = 0.859; Fig. 5.4b) and between 900 and 1100 m (p = 0.314; 0 to 29%)" (Gibson 2022) "*P. radiata* is a shade-intolerant species that requires open habitats for regeneration (Richardson 1998). We expected that in a fragmented forest, edge could create an appropriate scenario for a successful germination and recruitment. Results however, depicted more complex biological response of this tree species. First, while we detected germination differences between the Reserve and forest fragments, we detected no differences in terms of seedling recruitment. That is, if abiotic differences between the Reserve and forest fragments were relevant for seed germination (being germination higher at the Reserve), they became irrelevant for seedling recruitment. Secondly, while we detected that in the Reserve seed germination increased significantly, presumably due to a more soil moisture (Henriquez 2002), we also detected that seedling recruitment and concomitantly, seedling abundance decreased dramatically presumably due to a more shaded environment that constrained plant growth (Henriquez 2002)." (Bustamante and Simonetti 2005) "Previous research conducted less than 100 km north to our study site and with a similar patch mosaic (Bustamante et al. 2003) has documented an active invasive process of the Monterrey pine only in forest fragments sustaining intense disturbance, i.e. recent anthropogenic fires and logging. In contrast, in fragments with low disturbance, i.e., with large native adult trees and with a dense canopy, pine invasion occurs only at the edges (Bustamante et al. 2003). These observations agree with the general hypothesis that invasiveness of forest fragment is a function of structural aspects of forests such as cover and disturbance regime (Brother and Spingarn 1992; Laurence 1997). In this context, seeds of Monterrey pine arrive to the interior of well-structured forest fragments (as we have documented), nevertheless, they fail to establish due to abiotic constrain to seedling establishment prevailing there. Thus, these fragments become important for conservation

Species	Common	Seedling survival
		purposes as they still retain the original abiotic conditions of native forests, and therefore preclude plant invasion (Turner and Corlett 1996)." (Bustamante and Simonetti 2005) "By the end of the experiment, browsed seedlings reached 92.5% for *P. radiata* and 57.5% for *E. globulus*. Considering each vegetation patch and habitat separately, browsing on *P. radiata* was 100% in both vegetation patch-types in the mesic habitat and 90% and 80% in open sites and *Lithrea* patches, respectively in the xeric habitat (Fig. 1). Browsing on *E. globulus* showed a different pattern: it reached 90% in both vegetation patch-types of the mesic habitat, but only 40% and 10% in open and *Lithrea* patches, respectively in the xeric habitat (Fig. 1). Thus, in *P. radiata* ($X^2 = 4.43$; $P = 0.035$) as well as in E. globulus ($X^2 = 19.79$; $P < 0.0001$), we observed significant differences between habitats in seedling browsing. Overall, browsing on both species was significantly higher in the mesic than in the xeric habitat (Fig. 1). In turn, we observed no significant difference in seedling browsing for *P. radiata* ($X^2 = 0.37$; $P = 0.545$) nor for *E. globulus* ($X^2 = 0.93$; $P = 0.336$) between vegetation patch-types. Also, no significant statistical interaction between habitat and vegetation patch-type was detected for *P. radiata* ($X^2 = 0.001$; $P = 0.999$) nor for *E. globulus* ($X^2 = 0.86$; $P = 0.352$). However, this is clearer in the case of *P. radiata* than for *E. globulus* (Fig. 1). It is probable that in the latter species there was a low statistical power to detect a significant interaction" (Becerra and Bustamante 2009) "We observed that vertebrate browsing had an important negative effect on seedling survival of both *P. radiata* and *E. globulus*. This effect was stronger in *P. radiata* than in *E. globulus* as differences between survival curves of excluded and non-excluded seedlings for all monitoring times were greater in *P. radiata* than in *E. globulus*. Significant effects of vertebrate herbivory on seedling establishment of these species have already been documented in forestry plantations (Ferriere et al., 1983; Muñoz and Muruá, 1990; Richardson and Bond, 1991; O'Reilly and McArthur, 2000; McArthur and Appleton, 2004). However, our results suggest that in natural plant communities with higher woody plant cover than forestry plantations, vertebrate herbivores may strongly reduce the chances of seedling establishment of *P. radiata* and *E. globulus*. In addition to these general findings, we also observed some species-specific differences with respect to the effect of herbivory on seedling survival. While the effect of herbivory on seedling survival of *P. radiata* was significant throughout the different vegetation and habitat conditions, the role of herbivory on *E. globulus* survival differed depending on the vegetation patch-type and habitat. In this case, herbivory on *E. globulus* was significant only in open sites of the mesic habitat. The absence of differences in survival between protected and unprotected seedlings of *E. globulus* in both vegetation types of the xeric habitat could have been produced by the low rate of browsing observed on seedlings of this species in general in this habitat. In contrast, in spite of the high browsing on *E. globulus* seedlings observed in *Lithrea* patches of the mesic habitat, survival of protected and unprotected seedlings did not differ, due to high mortality of protected seedlings. This could have been produced by low light availability under *Lithrea* patches. In this case, it is possible that abiotic factors overshadowed herbivory effects. Similarly, other studies have also documented an important role of habitat, plant productivity or vegetation physiognomy in modulating the importance of the effect of herbivory on performance of native and

Species	Common	Seedling survival
		exotic plants (Fuentes et al., 1986; Hobbs, 2001; Fowler, 2002; DeWalt et al., 2004; Kuijper et al., 2004)." (Becerra and Bustamante 2009) "Our observations indicate that the main seedling browser on our study site is the European rabbit. The higher seedling browsing level in the mesic habitat in both species contrasts with a previous study which documented higher browsing on native trees by this herbivore in xeric habitats of central Chile (Fuentes et al., 1983). We cannot infer differences in rabbit abundance between habitats based on frequency of faeces due to possible differences in faeces decay rates between them (Simonetti, 1989). Even, if faeces frequency were an efficient indicator of rabbit abundance, rabbit populations should be higher in the xeric habitat and not in the mesic habitat where browsing was higher. Thus, difference in rabbit abundance between habitats is only a possible cause for the different seedling browsing levels between habitats, which should be evaluated more directly. On the other hand, other studies have found that rabbits have preferences for certain plants (Crawley, 1990). Thus, the higher seedling browsing observed in the mesic habitat may be related to a lower availability of some of their more important and preferred food sources (e.g., some herbs) in this habitat, which might have forced rabbits to feed on these exotic trees there." (Becerra and Bustamante 2009) Of planted seedlings... Ribbonwood *P. attenuata* × *P. radiata* 86% survival at age four *P. attenuata* 92% survival at age four *P. radiata* 22% survival at age four Balmoral Station *P. attenuata* × *P. radiata* 83% survival at age four *P. attenuata* 91% survival at age four P. radiata 31% survival at age four Eyrewell *P. attenuata* × P. radiata 95% survival at age four *P. attenuata* 81% survival at age four *P. radiata* 84% survival at age four (Dungey et al.2011) "Kaikohe District...The most common pine is *Pinus radiata*, seed sources mainly farmers' plantings. Recent regeneration of exotic trees occurs only on the open site such as road verges, burnt or cleared land, or where there is erosion. All the evidence points to the fact that older regeneration occurred when the bush areas were open, due to clearance of land by logging and or burning, or where scrub has been kept open by sporadic grazing." (Chavasse 1979)

Species	Common	Seedling survival
		"Observations of invasive radiata pine extend nearly the full latitudinal range of New Zealand (Fig. 1a), and were present between 1 and 1060 m elevation, 6–16 °C mean annual temperature, and 548–2813 mm annual precipitation." (Bellingham et al.2023) "The climatically suitable areas for radiata pine were in the warmer and drier regions of New Zealand, which is consistent with radiata pine's native range in coastal southern California, with only the coldest and wettest climates of New Zealand predicted to be outside the fundamental niche (Fig. 1b). " (Bellingham et al.2023) "Of 101 relevé plots nationally that we were confident contained invasive radiata pine, 56 had been collected in a manner consistent with those supporting previous quantitative vegetation classification. Of the 56 plots with suitable data, 31 (55%) could be classified to a previously defined vegetation type, whereas the composition of the remainder was not consistent with previously defined vegetation types. Instead, these were assigned to physiognomic types (Table 1). There were an equal number of plots in grasslands, fernland and herbfields versus successional shrublands in which radiata pine had invaded (21 plots in each of the groups, both 38% of the total) and fewer plots in forests were invaded (14 plots, 25% of the total)." (Bellingham et al.2023) Radiata pine often invades with other Pinaceae species during primary succession (Table 3). On volcanic substrates, it is more common than *Pinus pinaster* as an invader of lava and scoria on Rangitoto (Brown and Wilcox 2007) and mainly invades scoria at lower elevations on Mount Tarawera (Table 2). Much of New Zealand is mountainous and landslides are common because of unstable underlying bedrock, tectonism, and high rainfall events and storms including cyclones (e.g., Marden and Rowan 1993). Radiata pine is often planted to reduce the likelihood of landslides in erosion-prone terrain, yet it can invade landslides that form within extensive areas of natural forest (>2000 km^2; Table 3). Radiata pine has been widely planted on mobile coastal sand dunes, initially to stabilize them to prevent sand movement into agriculture, and later, once pine growth rates were found to be rapid, as a timber crop (McKelvey 1999). Seedlings of radiata pine establish on stable sand, and this study supports Wardle's (1991) prediction that, wherever there is a seed source in areas with 500–6000 mm annual rainfall, radiata pine will increasingly dominate primary succession on coastal sand dunes (Table 3)." (Bellingham et al.2023) "Secondary successions invaded by radiata pine are often in areas previously used for agriculture and then either abandoned or farmed less intensively (Standish et al. 2008; Wilson 2008). Widespread successions through native Myrtaceae shrubs and trees (*Lepospermum scoparium* and *Kunzea* spp.; Wardle 1991) are also commonly invaded by shade-intolerant radiata pine (Tables 1, 4); the low leaf area of these Myrtaceae species (Whitehead et al. 2004) may permit its establishment. Recurrent fire is likely to have promoted radiata pine invasions in some secondary successions by retarding succession, reducing leaf area, and presenting open sites favourable for the establishment of radiata pine (Druce 1957; Wassilief 1982; Wardle 1991; Wyse et al. 2018). Enhanced propagule pressure after establishment of new radiata pine plantations near invaded successional vegetation, from the late 1970s onward, is a probable reason for ongoing invasion, e.g., in Abel Tasman National Park (https://www.janszoon.org/assets/documents/Wilding%20conifer%20control%20.pdf) and the Marlborough Sounds (Marlborough District Council 2015). When uncontrolled in secondary successions, radiata pine can dominate, forming tall, closed canopy forests, e.g., c. 40 years after agriculture was abandoned on Kawau Island (Gardner 1993) (Bellingham et al.2023)

Species	Common	Seedling survival
		"Wildlings of *P. radiata* were found in all boundaries inspected, with a total of 1215 individuals recorded. The greatest density of wildlings occurred at the forest edge (first 5 m of forest) with this density exponentially declining (r^2 = 0.868) with distance into the forest (Fig. 2a). Both forest types (jarrah and karri forests) displayed a similar pattern of declining wildling density with distance into the forest, although wildling densities were consistently lower in karri relative to jarrah forest (Fig. 2b and c). This pattern was also consistent across the various age classes, although the older classes (10–19 years and 20 + years) tended to be more consistent in terms of density with distance from edge (less sharp decrease with distance), especially between 30 and 100 m from the edge (Fig. 2). Densities of younger wildings (1–3 and 4–9 years old) were generally similar and far greater than older age classes (10–19 years, 20 + years; Figs. 2 and 3). Overall, wildling density was greater in jarrah forest (mean 70.7 wildlings ha^{-1}) compared to karri forest (mean 24.7 wildlings ha^{-1}; t = 2.55; p = 0.021; df = 18). This trend of greater wildling density in jarrah compared to karri forest was consistent across all age classes (1–3 years, 4–9 years, 10–19 years) except for older trees (20+ years) which had much the same wildling density in each forest type (t = 0.26; p = 0.80; df = 20). There were also significantly more wildlings at the jarrah forest edge (within first 5 m of forest) and within the first 20 m of jarrah forest (p = 0.014 and p = 0.0079 respectively) compared to those distances in the karri forest. Site variables time since last fire, disturbance level and margin width (distance from the plantation edge to the native forest edge) were not different between these two forest types; however, jarrah forest had significantly lower understorey cover (mean cover class 2.23 vs 3; t = 2.161; p = 0.041; df = 23) and lower mean time since pine plantation establishment (44 years vs 63 years; t = 2.17; p = 0.041; df = 21)" (Calviño-Cancela and van Etten 2018) "Exclusion of rabbits had a significantly positive effect on seedling survival at both sites (Fig. 6a, b). Evidence of browsing was confined to the unfenced plots and took the form of shoot decapitation" (Davis et al.1996)
Pinus x attenuata	knobcone	"The proportion of emerged seedlings differed among microhabitats (p < 0.05) with strong evidence of an interaction between elevation and microhabitat (p < 0.05; Table 4.1; Fig. 4.1). Emergence within each microhabitat was lowest at 600 m, with similar proportions among elevations (p > 0.123) with the exception of disturbed plots at 1100 m (p = 0.020) and tussocks at 900 m (p = 0.015). The proportion of emerged seedlings was lowest in disturbed plots (0.01 – 0.10) and highest in tussocks (0.12 – 0.39) among all three elevations. Emergence within disturbed microhabitats was positively associated with elevation, while emergence was highest within undisturbed plots at 1100 m, and within tussocks and shrubs at 900 m. The proportion of seedling establishment (survival post winter of 2020) differed among elevations and across microhabitats with evidence of elevation interacting with both microhabitat and taxon (p< 0.05, Table 4.1; Fig. 4.2). Establishment was greatest overall at 900 m (0.33), followed by 1100 (0.32) and 600 m (0.26). The proportion of seedling establishment within disturbed and undisturbed plots was highest at 600 m with significant reductions in undisturbed plots at higher elevations (≥ 0.54; p ≤ 0.006; Fig. 4.2a). Establishment within tussocks was significantly higher at 900 m compared to 600 m (p = 0.004), while establishment within shrubs was positively associated with elevation (p < 0.001). The establishment of both P. radiata seed sources was similar among the three elevations (p≥ 0.497; Fig. 4.2b) in contrast to the establishment of P. radiata × P. attenuata seedlings which were positively associated with elevation (p ≤ 0.010)." (Gibson 2022)

Species	Common	Seedling survival
		"The proportion of emerged seedlings differed among microhabitats ($p < 0.05$) with strong evidence of an interaction between elevation and microhabitat ($p < 0.05$; Table 4.1; Fig. 4.1). Emergence within each microhabitat was lowest at 600 m, with similar proportions among elevations ($p > 0.123$) with the exception of disturbed plots at 1100 m ($p = 0.020$) and tussocks at 900 m ($p = 0.015$). The proportion of emerged seedlings was lowest in disturbed plots (0.01 – 0.10) and highest in tussocks (0.12 – 0.39) among all three elevations. Emergence within disturbed microhabitats was positively associated with elevation, while emergence was highest within undisturbed plots at 1100 m, and within tussocks and shrubs at 900 m. The proportion of seedling establishment (survival post winter of 2020) differed among elevations and across microhabitats with evidence of elevation interacting with both microhabitat and taxon ($p< 0.05$, Table 4.1; Fig. 4.2). Establishment was greatest overall at 900 m (0.33), followed by 1100 (0.32) and 600 m (0.26). The proportion of seedling establishment within disturbed and undisturbed plots was highest at 600 m with significant reductions in undisturbed plots at higher elevations (≥ 0.54; $p \leq 0.006$; Fig. 4.2a). Establishment within tussocks was significantly higher at 900 m compared to 600 m ($p = 0.004$), while establishment within shrubs was positively associated with elevation ($p < 0.001$). The establishment of both P. radiata seed sources was similar among the three elevations ($p\geq 0.497$; Fig. 4.2b) in contrast to the establishment of P. radiata × P. attenuata seedlings which were positively associated with elevation ($p \leq 0.010$)." (Gibson 2022) "Seedling survival in the first year exceeded 93.0% among all elevations for both caged and uncaged P. radiata seedlings (Fig. 5.1a). In the second year, all seedlings survived with the exception of one caged P. radiata at 1100 m (Fig. 5.1c).The relative SBD growth was similar between caged and uncaged seedlings ($p > 0.05$; Table 5.1; Figure 5.2a) and among elevations ($p > 0.05$). In contrast, the relative height increase in the first year differed between caged and uncaged seedlings ($p < 0.05$; Table 5.1; Fig. 5.3a) and among elevations ($p < 0.05$), with moderate to strong evidence of an interaction between cage treatment and elevation ($p < 0.05$). The relative height increase of caged seedlings was 34% greater than uncaged seedlings at 600 m ($p < 0.001$) and similar among 900 and 1100 m ($p > 0.755$). Among elevations, the relative height increase at 600 m was 72 and 81% greater than uncaged and caged seedlings at 1100 m, respectively ($p \leq 0.033$), while height at 900 m was 64 and 62% greater than at 1100 m, respectively ($p \leq 0.098$). The relative height increase in the second year only differed among elevations ($p < 0.05$; Table 5.1; Fig. 5.3c). The height increase of seedlings at 600 m was 50 to 64% and 71% greater than at 900 and 1100 m, respectively ($p \leq 0.002$), while the height increase of uncaged P. radiata at 900 m was 43% greater than at 1100 m ($p = 0.010$). The presence of frost damage on seedlings was similar between caged and uncaged ($p = 0.581$), among elevations ($p = 0.229$), and their interaction ($p = 0.233$). The proportion of seedlings with frost damage varied between 62-70% for caged and 65-82% for uncaged, with 67-72% among elevations"(Gibson 2022) "Survival of uncaged P. radiata seedlings ranged between 93.3 and 98.3%, while survival of uncaged *P. radiata* × *P. attenuata* seedlings was 100% (Fig. 5.1b). In the second year, all seedlings survived with the exception of one uncaged *P. radiata* × *P. attenuata* at 600 m (Fig. 5.1d). Herbivory is unlikely the cause of mortality for either taxon in either year as none of the dead seedlings showed signs of herbivory. The relative SBD growth differed between taxa ($p < 0.05$; Table 5.1; Figure 5.2b) with moderate evidence of an interaction between taxon and elevation ($p < 0.05$). SBD growth for *P. radiata* × *P. attenuata* seedlings was 36 to 47%

Species	Common	Seedling survival
		greater than for *P. radiata* seedlings across all elevations (p < 0.001). Compared to those at 600 m, the relative SBD growth of *P. radiata* × *P. attenuata* seedlings decreased by 27% at 900 m (p = 0.424) and 43% at 1100 m (p = 0.072). For *P. radiata* seedlings, SBD " (Gibson 2022) "The incidence of herbivore damage on uncaged *P. radiata* and *P. radiata* × *P. attenuata* seedlings in the first year was similar between the two species (p = 0.537; Fig. 5.4a) yet differed among elevations (p = 0.038). Herbivore damage was found on 40 to 45% of seedlings at 600 m compared to 0 to 3% at 900 m (p = 0.049) and 10 to 12% at 1100 m (p = 0.201. Incidence was similar between 900 and 1100m (p = 0.437). In the second year, the incidence of herbivore damage was similar between taxa (p = 0.859; Fig. 5.4b) and between 900 and 1100 m (p = 0.314; 0 to 29%)" (Gibson 2022) Of planted seedlings... Ribbonwood (700 masl) *P. attenuata* × *P. radiata* 86% survival at age four *P. attenuata* 92% survival at age four *P. radiata* 22% survival at age four Balmoral Station (730 m asl) *P. attenuata* × *P. radiata* 83% survival at age four *P. attenuata* 91% survival at age four *P. radiata* 31% survival at age four Eyrewell (160m asl) *P. attenuata* × *P. radiata* 95% survival at age four *P. attenuata* 81% survival at age four *P. radiata* 84% survival at age four (Dungey et al.2011)
Pseudotsuga menziesii	Douglas fir	"Seedling growth the first year is indeterminate but relatively slow and limited generally by moisture" (Burns and Honkala 1990) "Seedlings of the variety *menziesii* normally survive best when the seed germinates on moist mineral soil, but menziesii will tolerate a light litter layer. Seedlings do not survive well, however, on heavy accumulations of organic debris. In contrast, seedlings of the variety *glauca* are favored by a duff layer, especially in the larch forests of northwestern Montana" (Burns and Honkala 1990) "First-year seedlings survive and grow best under light shade, especially on southerly exposures, but older seedlings require full sunlight." (Burns and Honkala 1990) "Browsing and clipping by hares, brush rabbits, mountain beaver, pocket gophers, deer, and elk often injure seedlings and saplings. Recent reports have indicated that such damage in western Oregon and Washington may strongly affect seedling survival in many plantations (7,61). In drier areas, domestic livestock have caused

Species	Common	Seedling survival
		considerable damage to variety glauca plantations by grazing and trampling seedlings."(Burns and Honkala 1990) "The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine < radiata pine (*P. radiata*) < European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) < Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993)." (Ledgard 2001) "Here, we investigated seed predation by deer mice (*Peromyscus maniculatus*) and its effects on recruitment of ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) seedlings in unburned and recently burned fire-adapted montane forests in west-central Montana, USA. Deer mice were almost twice as abundant in burned than unburned stands. Deer mouse removal of seeds from petri dishes was two times higher in burned than in unburned stands, and seed removal levels were 8% higher for ponderosa pine than for the smaller Douglas-fir seeds. In seed-addition experiments, emergence of seedlings in deer mouse-exclusion cages was almost six times higher in burned compared to unburned forest. In both burned and unburned forest, emergence was lower for ponderosa pine than for Douglas-fir. Seedling survival to establishment did not differ between conifer species but was considerably higher in burned than in unburned forest. However, effects of seed predation on recruitment prevailed over fire effects: in cages allowing access by deer mice, emergence and establishment were extremely rare for both conifer species in both burned and unburned forest. This research suggests that consumer interactions can substantially influence recruitment even in fire-adapted forest ecosystems." (Zwolak et al.2010) "Estimated abundance of deer mice was 1.6 times higher in burned compared to unburned forest in 2006 (22.6 6 0.9 vs. 14.3 6 0.5 mice/grid, mean 6 SE), and 1.8 times higher in burned compared to unburned forest in 2007 (54.2 6 2.8 vs. 29.5 6 2.7 mice/grid; Table 1)." (Zwolak et al.2010) "Seed removal at night was higher in burned vs. unburned forest, particularly in 2006 (fire and fire 3-year effects; Table 2a, Fig. 1a). In addition, more ponderosa pine than Douglas-fir seeds were removed at night (species effect; Table 2a, Fig. 1a). During the day, overall differences in removal between burned and unburned forest were not significant. However, in contrast to nighttime removal, daytime removal was less intense in burned vs. unburned forest in 2007 (fire 3-year effect; Table 2b, Fig. 1b). As in nighttime trials, removal was greater for ponderosa pine seeds compared to Douglas-fir seeds, though this was only significant in 2007 (species 3-year effect; Table 2b, Fig. 1b)." (Zwolak et al.2010) "Seedling emergence in cages without rodent access was considerably higher in burned vs. unburned stands (fire effect; Table 3), but this effect disappeared in cages with rodent access (rodent access 3 fire effect; Table 3). In cages without rodent access, 39% of seedlings emerged in burned forest vs. 7% in unburned forest, while in cages with access, 0% of seedlings emerged in burned forest vs. 0.9% in unburned forest (Fig. 2a). Overall, seedling emergence was lower for ponderosa pine compared to Douglas-fir (species effect; Table 3). The difference between conifer species was not affected by fire or by mice (fire 3 species and rodent access 3 species interactions were nonsignificant and eliminated from the final model). Seedling survival also differed strongly between burned and unburned forest ($z = 2.72$, $P = 0.006$; Fig. 2b). In 2007, 75% (55 out of 73) of

Species	Common	Seedling survival
		seedlings in burned forest survived until September, whereas survival observed in unburned forest was only 30% (eight out of 27 seedlings survived). In 2008, the overall pattern of higher survival in burned forest remained unchanged, but survival in both burned (30%, 23 out of 76 seedlings) and unburned (0 out of 10 seedlings) forest was lower than in 2007 ($z = -5.48$, $P < 0.0001$). Besides fire and year, no other factors were significant predictors of seedling survival." (Zwolak et al.2010) " In 2007, the proportion of seeds sown that reached the establishment stage when mice were excluded was ;26% for ponderosa pine and 34% for Douglas-fir in burned stands, compared to 1% and 4%, respectively, in unburned stands; mouse access reduced these values to 0% in burned stands and <1% in unburned forest. In 2008, establishment without mice was ~1% for ponderosa pine and 16% for Douglas-fir in burned stands, compared to <1% for both species in unburned stands; mouse access reduced these proportions to 0." (Zwolak et al.2010) "Mean seedling survival at the final assessment did not differ significantly between the two species (Douglas fir 36 ± 3.8%, Corsican pine 28 ± 3.0%), but there were highly significant ($P < 0.01$) interactions between species and site, and species and vegetation cover. Survival of Douglas fir seedlings was greater than for Corsican pine at Bealey, Cass and Okuti sites while survival of Corsican pine was greater at Eyrewell. Survival of the two species was similar at Ellangowan and Avoca (data not presented). Survival of Corsican pine seedlings was greatest in the open and declined progressively as canopy cover increased. This contrasted with Douglas fir where seedling survival was greatest at the edge position (Fig. 3). Seedling survival of Corsican pine was greater than for Douglas fir at the open position, whereas survival of Douglas fir seedlings was greater at the edge, moderate- and dense-canopy positions, though the difference was significant only at the dense-canopy position (Fig. 3)" (Davis et al.2011) Five years after planting [underplanting/shade], the survival of SS [sitka spruce], NS [Norway spruce] and DF [Douglas fir] was all in the region of 95 per cent, comparable with 5-year survival of 96 per cent on the open-grown sites at the nearby Experiment 2. (Stokes et al.2021) "Seedling mortality 2 years after planting varied according to site location, with more mortality occurring on the Road K site (14 -18 %) than on the older, more open Road M stand (6%) (Table 2). Although the mortality rate was twice as high on the Road K site, differences between the two species and the two growing seasons at each site were minor (less than 4% on average; Table 2). These low mortality rates can be explained partly by the exceptionally wet weather that prevailed in the area at planting time and throughout the spring of 1993. Partitioning mortality rates between RLI classes (Fig. 1) showed that nearly 70% of Douglas-fir mortality occurred at RLI < 0.20, while the mortality rate for western hemlock was only half as high (36%) at similar RLI levels and evenly distributed along the transect. " (Mailly et al.1997) "Survival was poor in the warm, very-low-light environment, and thinning was unnecessary. Indeed, no Douglas-fir seedling developed an epicotyl or survived longer than 15 weeks, and most died before 7 weeks. In contrast, incense-cedar mortality was slower and less severe (Figure 1). Surviving incense-cedar seedlings looked spindly and were very small (Table 2), but they developed epicotyls and produced normal juvenile foliage. Little mortality occurred in the cool, very-low-light environment (Figure 2). Incense-cedar seedlings grew significantly ($P < 0.01$) larger than Douglas-fir seedlings in this environment (Table 2). The incense-

Species	Common	Seedling survival
		cedars were almost twice as heavy as Douglas-fir seedlings after a seven-month growth period. This growth difference occurred in both roots and shoots, but it was most evident in root weight. Incense cedar roots averaged about two-and-one-half times as heavy as Douglas-fir roots. Shoot-to-root ratios were higher for the Douglas-fir seedlings" (Minore 1988) 1-year-old seedlings per acre when opening size was 30 feet; 60 feet; 90 feet: 112; 162; 288 (McDonald 1966) "Seedling survival was very low in holm-oak forests due to soil disturbance by native fauna. In this habitat, wild boars pull up more than 50% of seedlings 3 months after transplantation, and by the end of the experiment all seedlings had died. In heathlands and beech forests drought stress seemed to be the main barrier against seedling survival. In heathlands, only 4% of seedlings survived after the summer, while, in beech forests, seedling survival were less than 40% (Fig. 3). Overall, at the end of the experiment, seedling survival time was significantly different among habitats (X^2 = 319.8, df = 2, P < 0.0001). Survival time was longer in beech forests and shorter in holm-oak forests (Fig. 4). There were differences between species (X^2 = 25.4, P < 0.0001) with silver fir seedlings having longer survival time than Douglas fir. Likewise, these differences between species were also observed within habitats (beech: X^2 = 8.77, P = 0.003; holm-oak: X^2 = 11.6, P = 0.0006; and heathlands: X^2 = 6.05, P = 0.013) (Fig. 4). Due to high seedling mortality, seedling relative growth rate could not be analyzed in holm-oak forests. Overall, 5 months after transplantation, relative growth rate was very low in both species (Douglas fir: 0.009 ± 0.01; and silver fir: 0.022 ± 0.01 cm). There were no significant differences between species (F1, 468 = 0.75, P = 0.38) or between beech forests and heathlands (F1, 6 = 0.4, P = 0.55). In beech forests, relative growth rate was not significantly different between species, both 8 months after transplantation (F1, 234 = 0.68, P = 0.41) and at the end of the experiment (F1, 237 = 2.36, P = 0.12). Transition from seed to seedling Overall, the probability of one seed becoming an established seedling was very low for both conifer species (Fig. 5). In beech forests, approximately 4% of Douglas fir seeds and 5% of silver fir seeds of initial seed sets become established seedlings (Fig. 5a). In heathlands, Douglas fir showed a higher probability of survival than silver fir (0.4 and 0%, respectively) due to a higher germination rate, while in holm-oak forests, survival was null for both species" (Carrillo-Gavilán et al.2012) "The probability of invasion success of Douglas fir decreased along the sequential stages of establishment in all habitats, showing the best performance in beech forests. The higher germination capacity of Douglas fir seemed to predict a better establishment success compared to silver fir. However, pressures by native fauna and drought stress are potential mechanisms behind seedling mortality limiting their establishment of both conifer species. In Douglas fir, seed removal was not very intense in any habitat compared to its native range (Huggard and Arsenault 2009) or with other conifer species (Borchert et al. 2003; Peters et al. 2004; Carrillo-Gavilán et al. 2010). Seed removal was similar among habitats despite of the fact that the three habitat types analyzed were located at different altitudes. These results do not match with previous studies, which have observed that small mammal abundance decreases with altitudinal gradients (Torre and Arrizabalaga 2009). The low seed removal rates might be due to seed satiation (Stowe et al. 2000) as the experiment coincided with seed dispersal of many native plant species. Moreover, seed removers might have a higher preference either towards holm-oak acorns (Gómez 2004; Espelta et al. 2009) or beech nuts, which are larger than fir

Species	Common	Seedling survival
		seeds. Douglas fir germination rates were high and did not differ between habitats despite large differences in vegetation structure and light availability. This is in accordance with other field studies where Douglas fir seedling emergence was very homogeneous under different microsites (Dunne and Parker 1999). In spite of this, our seed germination rates should be considered with caution. Since they come from a nursery, our seed sample might be causing an overestimation of this parameter attributable to a higher quality of seeds. Nonetheless, seed germination was higher in Douglas than in silver fir. silver fir's sensitivity to other environmental stresses such as drought (Gradečki and Poštenjak 2001), might be the cause of its low germination rates. In this context, a recent review by Pyšek and Richardson (2007) reveals that alien species are generally reported to germinate earlier, better and in a wider range of conditions than native species. Since many seedlings disappeared in holm-oak forests due to soil disturbance by wild boars, native fauna might be a potential mechanism limiting the establishment of seedlings in this forest type. In contrast, in beech forests and in heathlands, seedling mortality due to summer drought stress (Alpert et al. 2000) was a prominent ecological filter for both native and alien plant species as has been reported in other Mediterranean regions (Dunne and Parker 1999; Rey and Alcántara 2000; Domènech and Vilà 2006)." (Carrillo-Gavilán et al.2012) "Climate change is causing significant shifts in tree species distributions to higher elevations and latitudes. Seed germination and seedling establishment are particularly important steps in tree range expansion under warmer conditions, yet seedling establishment is influenced by a range of factors beyond temperature, including herbivory, microenvironment, and the timing and amount of precipitation. We conducted an experiment to assess how augmented precipitation regimes, wildlife herbivory, and microclimate influence germination and first-season survival of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) near the upper elevational limit of its range in the southern Rocky Mountains. Germination was strongly influenced by moisture, with over three times higher germination in watered treatments. Seedling survival was similar across watered treatments but was negatively associated with microenvironments with higher maximum temperatures. These results indicate that soil moisture effects on germination and the negative impact of hot growing-season temperatures on seedling survival limit initial seedling establishment in Douglas-fir, even at the cooler and wetter end of its range, suggesting that the planting of this species will be most successful in cooler and wetter microsites. Taken together, this study suggests that continued warming and projected increases in droughts may strongly limit Douglas-fir regeneration and thus its ability to shift upwards with climate change." (Foster et al.2020) "The germination rate across all treatments for Douglas-fir was 17.6%, and survivorship of germinants was 82.8%, with 140 surviving individuals. Repeated-measures tests that found watering treatments were significantly correlated with the timing of germination ($p = 0.01$); nonwatered treatments germinated later than those that received supplemental water (Fig. 2). However, the biweekly ambient precipitation inputs were not associated with the timing of germination. Mean germination rates were significantly higher in the watered treatments, with germination 1.8 and 2.2 times higher in the 25% and 50% treatments, respectively, than in the control (drought) treatment (Fig. 3A). Once germinated, however, survival was high (>80%) across the caged control and both watering treatments (Fig. 3B). There were no significant effects of wildlife exclusion on germination or survival, though the mean rate of survival was substantially higher in the caged (81%) than in the uncaged control (59%) (Figs. 3A and 3B). Mean daily maximum temperature at the soil surface had a

Species	Common	Seedling survival
		strong negative association with survival (Fig. 3C). Neither temperature variable was associated with germination rates (Supplementary Table S11)." (Foster et al.2020) "Wide variations (37–93%) in the juvenile survival rate of Douglas-fir were mainly driven by early and late frost events (daily Tmin < 0 °C), summer drought, and continentality. Juvenile survival declined with an increasing number of frost events within the observation period and prevailing warm spells preceding the frost events. The seed origin of the tested provenances had a minor effect and was related to the altitude, but not to the variety or the climate of provenance origin." (Chakraborty et al.2019) "Mean survival rate of juvenile Douglas-fir trees varied significantly between provenance trials (Kruskal Wallis test; $p < 0.000$) and range from 37 to 93%, with a mean of 74.3% across all trials (Fig. 2). The GLMM explained around 64% of the variation in juvenile survival rate (Table 2). The most important late or spring frost-related variables were the number of LF days (LF1), the temperature difference between absolute LFtemperature minimum, and the mean temperature of the seven preceding days (LF12) and the number of vegetation days > 10° until the absolute LF temperature minimum (LF8) (Table 2). Significant early, respectively autumn frost variables were the number of EF days (EF1), the daily mean temperature of the EF day with the absolute EF temperature minimum (EF4), and the number of vegetation days > 5 °C until the absolute EF temperature minimum (EF7). The most important and significant climate variables describing the overall site climate were the summer heat moisture index SHM, which might be used to quantify xeric, but not necessarily drought conditions, and continentality, which is the difference between the warmest and coldest month temperature (Table 2)." (Chakraborty et al.2019) "In general, survival decreased with an increasing number of late and early frost days and with prevailing warmer conditions (vegetation days 5–10 °C) before the day of the respective extreme late or early frost event (Fig. 3; Table 2)." (Chakraborty et al.2019) "Exclusion of rabbits had a significantly positive effect on seedling survival at both sites (Fig. 6a, b). Evidence of browsing was confined to the unfenced plots and took the form of shoot decapitation" (Davis et al.1996) "A study of the survival of naturally disseminated tree seed was made in a clearcut area on the H. J. Andrews Experimental Forest in the Cascade Range of western Oregon during 1955-60. From start of seed fall until the end of germination in late spring following year, 12% of the Douglas-fir (*Pseudotsuga menziesii*) seed survived. Ground-feeding birds and small mammals caused 63% of the seed loss and other agents 25%. Thirty-one per cent of the seed of western hemlock (*Tsuga heterophylla*) lived from the start of seed fall until the end of germination. Of the amount lost, birds and mammals took 16% and all other factors 53%. A large proportion (65%) of western redcedar (*Thuja plicata*) seed survived during the same period. The entire loss was attributed to causes such as nonviable filled seeds, disease, invertebrates, and others. Ground-feeding birds and small mammals showed a definite preference for Douglas-fir seeds. Only about 25% as many hemlock seeds were taken, and redcedar was not consumed in appreciable amounts. Most of the seed depredations by birds and mammals occurred from start of seed fall to start of germination; other factors took heaviest toll during the germination period." (Gashwiler 1967)

Species	Common	Seedling survival
Larix decidua	European larch	"The most commonly planted conifers can be ranked approximately in terms of increasing natural regeneration vigour as follows: muricata (*P. muricata*) and ponderosa (*P. ponderosa*) pine <radiata pine (*P. radiata*) <European larch (*Larix decidua*) < Corsican pine (*P. nigra*) and Douglas-fir (*Pseudotsuga menziesii*) < Scots pine (*P. sylvestris*) < lodgepole pine. Lodgepole pine is now recognised as the most aggressive spreading conifer in New Zealand (Ledgard, 1988; Ledgard, 1993)." (Ledgard 2001)
Larix laricina	tamarack	"Eastern larch had the lowest altitudinal limit with all but one stem found below 625 m a.s.l.—the approximate Mealy Mountains tree-form line. Although eastern larch can occasionally layer, it does not have the growth plasticity of either black spruce or balsam fir to form krummholz; sexual reproduction is by far its dominant regenerative strategy (Elliott and Short 1979; Hustich 1953; Payette, Deshaye, and Gilbert 1982). With outlying stems at 691 m and 770 m a.s.l., eastern larch's threshold of tolerance appears to lie beyond the current Mealy Mountains treeline. These individuals, up to 2.2 km in distance from the closest cone-bearing eastern larch stem, highlight the ability of wind-dispersed conifer seeds to travel significant distances and establish in favorable microsites." (Trant et al.2018) "Only three seedlings emerged on feathermoss plots. Counts of new seedlings and mortality were not significantly higher on mineral soil plots on any given date. Cumulative emergence and mortality however were significantly greater ($P \leq 0.05$) in mineral soil plots; the ratio of seedlings to sown seed tended to be larger ($P \leq 0.10$) in mineral soil plots." (Brown et al.1988) Mortality % (SD) mineral soil 36.7 (5.7); feathermoss 0.0 (0.0); wetland trough 56.7 (23.4); wetland feathermoss 71.7 (15.3); wetland tussock top 68.8 (23.7) (Brown et al.1988)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	"Several insects are found on redwood but none cause significant damage." (Burns and Honkala 1990)
Sequoiadendron giganteum	Giant redwood	"Natural reproduction in giant sequoia is an unusually tenuous process. Of the enormous numbers of seeds shed each year, extremely few encounter the combination of conditions necessary to become successfully established seedlings." (Burns and Honkala 1990) "In contrast with most coniferous seeds, a large majority of seeds of giant sequoia die from desiccation and solar radiation soon after reaching the forest floor, especially during the summer. In one study, viability of seeds removed from fresh cones and placed on the ground dropped from 45 percent to 0 in 20 days. Seeds collected from the forest floor showed an average viability of 1 percent" (Burns and Honkala 1990) "Seeds dropped just before the first snow or just as the snow melts may have the best chance of germinating and becoming successfully established. Seedlings that produce roots early in the season during favorable soil moisture conditions are more likely to survive the dry summer. The first stage of germination-extension of the radicle-sometimes takes place beneath the snow" (Burns and Honkala 1990)

Species	Common	Seedling survival
		"Thick litter usually dries too quickly for seeds to germinate, and virtually all seedlings that do get started die before their roots can penetrate to mineral soil" (Burns and Honkala 1990) "After seedlings are established on more favorable seedbeds, a light covering of litter can moderate soil surface temperatures and retard drying" (Burns and Honkala 1990) "Seedlings rarely become established in dense grass cover, probably because moisture is depleted in the surface soil early in the season" (Burns and Honkala 1990) "Partially burned litter, in terms of its suitability for successful seedling establishment, ranks between undisturbed forest floor and areas subjected to hot fires. First-year giant sequoia seedlings established on treated-bulldozed or burned or both-areas were 30 to 150 times more numerous than those on undisturbed forest floor. Mortality of first-year seedlings during the 3 summer months on one treated area averaged 39 percent, with an additional 25 percent dying during the next 9 months. Desiccation was the primary cause of mortality in the summer. During a year of increased seasonal precipitation, mortality attributable to desiccation decreased, whereas that caused by insects increased to 25 percent of total mortality. Heat canker, damage by birds and mammals, and fungal attacks were of minor importance. In the same study, direct mortality of first-year seedlings from insect predation ranged from 3 to 18 percent of all seedlings present. Some of the significant additional insect damage probably caused delayed mortality " (Burns and Honkala 1990) "Insect depredations do not seriously harm giant sequoias older than about 2 years, although sometimes they may reduce vigor"(Burns and Honkala 1990)
Picea abies	Norway spruce	"Decreasing surface vegetation around seedlings tends to decrease seedling mortality and improve seedling growth at least a few years after planting (Munson et al. 1993; Nilsson and Örlander 1999; Örlander and Nilsson 1999; Knapp et al. 2008). During the present study period, however, the surface vegetation was still rather scant. The increased seedling mortality after the herbicide treatment in the second growing season (in Pieksämäki) suggests that seedlings have even suffered from the herbicide." (Heiskanen et al.2013) "The density of germinants and seedlings varied along the invasion gradient; it was lowest at the forest edge where the canopy of previously established trees was dense, somewhat higher in the relatively open grassland, and highest approximately in the center of the invasion front (Fig. 2). Although germinants and seedlings were distributed equally relative to the forest edge (mean distances to forest edge 95.7 m and 94.6 m; Fig. 2), their fine-scale spatial patterns progressively diverged with size-class. Germinant density was positively correlated with the density of seedlings <20 cm tall (partial Mantel $r = 0.28$, $P < 0.0001$), weakly positively correlated with the density of seedlings 20–50 cm tall ($r = 0.07$, $P < 0.0001$), and not correlated with the density of seedlings 50–130 cm tall ($r = 0.02$, $P < 0.20$)." (Dovčiak et al.2008) "Germinant density (mean ± SE; 4.6 ± 0.6 germinants m^{-2}) was only weakly positively related to seed rain which was on average >50 times greater and appeared to saturate vegetation plots with seeds. In contrast, several environmental variables were related to germinant density better than seed rain (Table 3). Overstory tree influence potential had the most negative effects on germinant density, thus negating positive effects of nearby trees as the seed source (c.f., Fig. 3). Shading by overstory trees could explain their negative effects only partially: germinant density correlated weakly positively with diffuse radiation and canopy openness but

Species	Common	Seedling survival
		weakly negatively with direct radiation (Table 3). Relative to light variables, germinant density was more positively related to soil moisture (Table 3), which was negatively correlated with tree influence potential (partial Mantel r = -0.38, P < 0.0001). However, of all variables, germinant density was most positively related to moss cover (Table 3), which was positively correlated with soil moisture (partial Mantel r = 0.39, P < 0.0001). In contrast, grass and Vaccinium cover appeared to influence germinant density negatively (Table 3). The main multivariate gradient driving the germinant density was that of increasing moss cover with decreasing tree influence potential (factor 2) while the strongest environmental gradient (factor 1) had only weak influence on germinant density as it integrated mainly the positive effects of diffuse radiation and canopy openness with the negative effects of grass cover (Table 3, Fig. 4)." (Dovčiak et al.2008) "Seedlings <0.2 m tall were most negatively related to tree basal area and grass cover, and they were positively related to light, but these relationships weakened as seedlings increased in height to >0.5 m (Table 4). In contrast, moss cover was related positively to seedling density similarly well across height classes (Table 4). Soil variables (including moisture) tended to be correlated positively with seedlings 0.5–1.3 m tall but unrelated or negatively related to seedlings <0.5 m tall. Both main multivariate gradients (related to tree basal area, grass cover, and light) correlated equally positively with the density of seedlings <0.2 m tall, suggesting that the overall positive effects of high light and low overstory basal area outweigh the negative effects of grass cover at this seedling life-stage (Table 4, Fig. 5). However, both gradients became less significant as seedlings increased in size, reflecting weaker relationships of taller seedlings to light and tree basal area. The weak gradient related to soil pH (factor 3) did not show a clear pattern" (Dovčiak et al.2008) "In both study years, mortality of seedlings within the total exclosures (i.e. control treatment) highly varied between the tree species and experimental sites (Fig. 1). In 2005, mean loss rates of spruce within the control treatment ranged from 3.0 up to 10.0 %. For fir, mean loss rates spanned between 50.1 and 68.0 % and for beech between 24.3 and 75.9 %. In the following year (2006), with only spruce and fir seedlings available, 0.0–23.3 % of spruce seedlings died on average in the control, whereas 10.0–26.7 % of fir seedlings got lost. In the treatments accessible only for invertebrates, we observed mean loss rates of spruce seedlings between 6.1 and 10.7 % in 2005, compared to 10-20 % in 2006. Loss rates of fir seedlings in the same treatment were between 30.0 and 57.7 % in 2005 and between 6.7 and 40.0 % in 2006. Referring values for beech seedlings were 6.0–55.7 % in 2005. Mean loss rates of seedlings in the ungulate/hare exclosures also showed a high variation: The values for spruce ranged from 0.0 up to 28.0 % in 2005 and from 0.0 to 40.0 % in 2006, for fir from 47.2 to 60.7 % in 2005 and from 0.0 to 46.7 % in 2006, and for beech from 14.7 to 47.2 % in 2005. The treatments accessible to all guilds of herbivores showed loss rates of spruce seedlings between 10.0 and 17.9 % in 2005 compared to 0.0–20.7 % in 2006, loss rates fir seedlings between 25.3 and 61.9 % in 2005 and 6.7–40.0 % in 2006, and beech seedlings between 9.0 and 41.1 % (2005). Summing up, loss rates showed high variation in terms of experimental sites, study years and trees species (Fig. 1). In the ZINB models, the count submodels' regression coefficients of the factor ''experimental site'' indicated significantly higher mortality rates in the large old-growth forest (LOF) in both study years compared to the small old-growth forest (SOF; Table 2). In 2005, we additionally observed significantly lower mortality rates in the managed forest (MF) compared to both old-growth forest sites. As for the tree species, model ''2005'' yielded a higher, positive regression coefficient (i.e. higher loss rates) for fir, followed by beech and spruce. Moreover, significantly higher loss rates

Species	Common	Seedling survival
		occurred within the total exclosures than in the mammal exclosures and on open access plots, whereas total exclosures and ungulate/hare exclosures did not significantly differ in seedling loss rates. For the second study year (model ‘‘2006’’), spruce again showed lower loss rates than fir interacting with the treatment. Contrary to the model ‘‘2005’’, ungulate/hare exclosures were characterized by higher seedling loss rates compared to mortality rates in the total exclosures, whereas open access plots and mammal exclosures did not differ from total exclosures. Calculating the referring IRR, the interaction of tree species and treatment indicated higher losses of fir on open access (22 %) and in ungulate/hare exclosure plots (16 %) than in total exclosures and lower losses in mammal exclosures (19 %) than in total exclosures. Within the total exclosures, a higher portion (57 %) of fir seedlings died compared to spruce, which was also the case within total exclosures, where 35 % more fir than spruce seedlings died. As mentioned, both years’ zero-inflated negative binomial models performed significantly better than the pure negative binomial models, indicating that full survival of clusters of seedlings (each containing one tree species, respectively) and loss of seedlings were two distinct processes. For 2005, complete cluster survival was lower for fir than for beech and for spruce. In 2006, survival was a function of the experimental site with significantly lower complete cluster survival on LOF compared to SOF (Table 2). We calculated relative trapping success in numbers of captured individuals per 100 trapping nights. We included recaptured individuals to represent feeding pressure on tree seedlings in a more realistic way than with pure numbers of newly caught specimen. In the study years 2005 and 2006, trapping success was low following a peak year of small mammal abundance in 2004 (Table 3). Two species of potential seedling predators (rodents) were caught in the study area during the study period 2005–2006, i.e. the yellow-necked mouse and the bank vole." (Nopp-Mayr et al.2015) "To our knowledge, our study is the first to describe the regeneration dynamics of Norway spruce in North America. In the plantation surroundings, most Norway spruce regeneration was found near the edge and on a few sites beyond the plantation border, where it spread mostly in open and disturbed areas such as recent clearcuts adjacent to the studied plantations. In our preliminary study involving a 23 plantations in Quebec (Mottet et al., 2010), we reported a low probability (<2%) of finding natural Norway spruce regeneration beyond the plantation border. However, the fact that this preliminary study did not include surveys in clearcut areas may explain the low occurrence of Norway spruce regeneration. In the present study, since surveys were undergone using small plots placed at most 28 m from the plantation edge, we could not evaluate the rare occurrence of regeneration, nor the maximal spread distance of Norway spruce. Although Norway spruce seeds are known to have a limited effective dispersal range (in general, one to two tree lengths from the stand edge; Hanssen, 2003; Rozman et al., 2015), long-distance dispersal on snow may occur in open areas where wind velocity is high (Greene et al., 1999)." (Mottet et al.2021)
Picea engelmannii	Engelmann spruce	Of *P. engelmanii*, "Survival also was better on the north aspect than on the south aspect (table 2). However, total survival on the north aspect at the end of the study was only 1.4% of the viable seeds sown. Seedlings that survived through the fifth growing season generally survived to the end of the study. In most years, survival was significantly improved by scarification, by shade, and by the combination of scarification and shade. The scarification x years interaction and the differences in survival between years also were significant {Alexander 1984). On the south aspect, total survival was only 0.2% of the viable seeds sown (table 2).

Species	Common	Seedling survival
		Although seedlings that survived through the fifth growing season generally survived to the end of the study, there was no survival on any of the seedbed treatments for seeds sown after 1975. In those few years when seedlings survived beyond the first year, shade and the combination of shade and scarification significantly improved survival. The shade x years interaction was significant, indicating high variability between years (Alexander 1984). Seventy-six percent of the seedlings that germinated on the north aspect died by the end of the study. About two-thirds of the total mortality occurred the first year (table 3). On the south aspect, 95% of the seedlings were dead by the end of the study, with more than 90% of the total mortality occurring the first year (Alexander 1984). Drought was the most significant cause of mortality on both aspects, followed by clipping by birds (table 4). On the north aspect, these two factors plus frost heave and snowmold accounted for nearly 90% of the mortality. On the south aspect, drought, clipping, and heat girdle accounted for about 90% of the mortality (Alexander 1984)." (Alexander 1986) "Engelmann spruce and subalpine fir establishment events typically occurred in years of above-average snowpack (SWE SEA for spruce: $P < 0.10$, fir: $P < 0.05$, Fig. 3A, B) and with cooler and wetter summer conditions (SPEI SEA establishing by species; Fig. 3C, D, G, H). Specifically, establishment events coincided with greater snowpack (Mann–Whitney U: spruce $P < 0.05$, fir $P < 0.05$, Fig. 3C, D) and cooler and wetter summer conditions (positive SPEI) during the months of June (Mann–Whitney U: spruce $P < 0.01$, fir $P < 0.01$) and July (Mann–Whitney U spruce: $P < 0.01$, fir $P < 0.01$) (Fig. 3G, H)." (Andrus et al.2018) "Over the past 70 years, Engelmann spruce and subalpine fir established episodically with strong synchrony across the study area. Consistent with our hypothesis, broad-scale establishment events occurred during years of anomalously high soil moisture availability from above-average snowpack and/or cool and wet summer climatic conditions. A decrease in the number of fir and spruce establishment events from 1975 to 2010 coincided with declining snowpack (Clow 2010) and a multi-decadal trend of rising summer temperatures and increased moisture deficits (Andreadis and Lettenmaier 2006). In the context of increasing climate-driven tree mortality at or near our sample sites over the period from 1982 to 2013 (Smith et al. 2015), our results suggest that seedling establishment will also be negatively impacted by climate warming in systems with water-limited growing seasons across western North America. Collectively, these shifts in population dynamics of subalpine forests may reduce tree density or could result in a shift in vegetation type (e.g., forest to woodland) at some sites" (Andrus et al.2018)
Picea sitchensis	Sitka spruce	"Sitka spruce is damaged at various locations by animals such as elk, bear, deer, porcupines, rabbits, hares, and squirrels. In general, these problems are more serious in the southern part of the range. Deer are generally more troublesome in the southern part, porcupines in the northern part (25). Spruce is often less damaged than its associates" (Burns and Honkala 1990)
Abies grandis	grand fir	"Studies of seedling survival indicate that more than 30 percent of grand fir seedlings die in the first season, and an additional 10 percent die in the second season. Losses drop off rapidly after the first 2 years, and seedlings 3 years old are fairly well established" (Burns and Honkala 1990)

Species	Common	Seedling survival
		"Initial survival and growth of grand fir are favored by a moderate overwood shade. Under full sun it is largely subordinate to faster growing, shade-intolerant species." (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Seedling establishment in small experimental plots under a natural canopy was most common where soil had been disturbed but did occur in natural litter; after three growing seasons, only 5 percent of the germinants survived in the most favorable soil conditions." (Burns and Honkala 1990) "*Phytophthora cinnamomi* causes major losses to some nurseries and cultivated trees. A white pocket top rot, caused by an unidentified fungus, is a serious problem. Losses to other diseases and to insects are minor. Animal damage to planted seedlings is highly variable, sometimes more and sometimes less than on associated conifers."(Burns and Honkala 1990)
Thuja plicata	western red cedar	"Most seeds escape rodent and bird predation, but seedling mortality is high during the germination period " (Burns and Honkala 1990) "Partial shade is beneficial because drought and high soil temperature damage seedlings in full sunlight, and poor root penetration causes damage from drought in full shade." (Burns and Honkala 1990) "Western redcedar suffers little damage from insects, but it is a host for several economically important insect species." (Burns and Honkala 1990) "More than 200 fungi are found on western redcedar, but it is less susceptible to pathological attacks than are most of its associates." (Burns and Honkala 1990) "Redcedar seedlings and saplings are often severely browsed by deer, elk, or rodents, and browse damage may be the most important stand-establishment problem." (Burns and Honkala 1990) "Although redcedar had uniformly high survival in both edge and interior plots, there was a small but statistically significant reduction in survival for seedlings with the browsing protection treatment in interior plots ($p = 0.042$). We did not detect a significant effect of fertilization on redcedar survival (Fig. 2)." (Weber et al.2017) "Reasons for the relative absence of Thuja plicata regeneration in the old growth *Thuja plicata* - *Tsuga heterophylla* forests close to Vancouver, British Columbia, were assessed by measuring seedfall and applying Thuja seeds to small plots. All measurements were replicated in two different sites. The small (0.5 m2) plots were established in 2 canopy cover conditions (clearcut and forest), 3 seedbed conditions (mineral soil, burned forest floor, and undisturbed forest floor), and 2 mammal and bird seed predation conditions (with and without).

Species	Common	Seedling survival
		Each canopy cover, seedbed, and seed predation combination was replicated 15 times in each study site. Large numbers of viable seeds (>200/m^2) fell in 1990/91 and again in 1994/95. Seed germination decreased in the order - burn > mineral soil > forest floor; forest > clearcut; and without predation > with predation. After 3 growing seasons of the 100 seeds applied to each plot, an average of only 1-2 seedlings had survived. This number of surviving seedlings decreased in the order- burn > mineral soil > forest floor, and clearcut > forest, but was not influenced by predation. After 3 growing seasons, seedling growth tended to decrease in the order - burn > forest floor > mineral soil; clearcut > forest; and without predation > with predation. It was concluded that the relative lack of regenerating Thuja seedlings in the study area forests was not due to a lack of viable seeds. Although a lack of suitable seedbeds and the presence of the forest canopy reduce the number of seedlings in undisturbed forests, this number should still be substantial. The observed relative lack of regenerating Thuja seedlings must therefore result from other factors which were not considered in the present study." (Feller and Klinka 1998)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S9. Terminal velocity

Species	Common	Terminal velocity
Pinus contorta	lodgepole	0.68 ± 0.005 m/s (Wyse and Hulme 2021) 0.893 ± 0.131 m/s (Vander Wall 2003) 0.892 ± 0.143 m/s (Johnson et al.2003) 0.6-0.8 (Siggins 1933: in Critchfield1980) 0.6-0.8 (Cremer 1971: in Critchfield1980)
Pinus sylvestris	Scots	0.65 ± 0.005 m/s (Wyse and Hulme 2021) 0.738 ± 0.006 m/s (Debain et al.2003)
Pinus mugo complex	mountain	0.92 ± 0.011 m/s (Wyse and Hulme 2021)
Pinus nigra	black, Austrian	0.80 ± 0.008 m/s (Wyse and Hulme 2021) 0.85 ± 0.07 m/s (Caplat et al.2012)
Pinus ponderosa	Ponderosa	0.91 ± 0.009 m/s (Wyse and Hulme 2021) 0.978 ± 0.171 m/s (Vander Wall 2003) 0.986 ± 0.189 m/s (Johnson et al.2003)
Pinus muricata	bishop	0.80 ± 0.005 m/s (Wyse and Hulme 2021)
Pinus pinaster	maritime	0.88 ± 0.007 m/s (Wyse and Hulme 2021)
Pinus radiata	Monterey	0.94 ± 0.007 m/s (Wyse and Hulme 2021) 0.91 m/s (Wyse et al.2019)
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	1.28 m/s (Lynch 2023)
Larix decidua	European larch	0.96 ± 0.14 m/s *Larix kaempferi* (Lee et al.2022)
Larix laricina	tamarack	0.96 ± 0.14 m/s *Larix kaempferi* (Lee et al.2022)

Species	**Common**	Terminal velocity
Larix occidentalis	western larch	0.96 ± 0.14 m/s *Larix kaempferi* (Lee et al.2022)
Sequoia sempervirens	Coastal redwood	Ave = 2.6 m/s (Burns and Honkala 1990)
Sequoiadendron giganteum	Giant redwood	
Picea abies	Norway spruce	
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	0.53 ± 0.04 (Kaliniewicz and Kusińska 2018)
Abies grandis	grand fir	1.10 ± 0.09 m/s *Abies koreana* (Lee et al.2022)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	2.66 ± 0.33 m/s *Chamaecyparis obtusa* (Lee et al.2022)
Thuja plicata	western red cedar	1.25 m/s *Thuja occidentalis* (Lee et al.2022)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	*Cedrus* > *Abies* (Dagher Kharrat et al.2018)

S10. Dispersal

Species	Common	Dispersal
Pinus contorta	lodgepole	"Density of seedfall 20 m (66 ft) from the timber edge is only 10 to 30 percent of that at the timber edge for stands in the Rocky Mountains (fig. 2) (42). Dispersal of sufficient seed to adequately restock an area often is only about 60 m (200 ft) (23,38). Prevailing winds, thermal effects, or scudding on the snow may disperse seeds far beyond these distances, however." (Burns and Honkala 1990) "For example*, P. contorta* wildlings dispersed from Mid Dome plantations in Southland indicate that in most years seedlings establish 4.5 km, and in some years 8 km, downwind from the source (P. D. Chapman, pers. comm.)" (Hunter and Douglas 1984) "We asked how propagule pressure varied with time since last fire, how seed delivery into burned forest varied with age and structure of live forest edges, what variables explained seed delivery into burned forest, and how spatial patterns of delivery across the burned area could vary with alternate patterns of surrounding live forest age. Seeds were collected in traps along 100-m transects (n = 18) extending from live forest edges of varying age (18, 30, and >100 yr) into areas of recent (2-yr) high-severity fire, and along transects in live forests to measure propagule pressure. Propagule pressure was low in 18-yr-old stands (~8 seeds/m^2) and similarly greater in 30- and 100-yr-old stands (~32 seeds/m^2). Mean dispersal distance was lowest from 18-yr-old edges and greatest from >100-yr-old edges. Seed delivery into burned forest declined with increasing distance and increased with height of trees at live forest edges, and was consistently higher for *P. contorta* than for other conifers. Empirical dispersal kernels revealed that seed delivery from 18-yr-old edges was very low (≤2.4 seeds/m^2) and concentrated within 10 m of the live edge, whereas seed delivery from >100-yr-old edges was >4.9 seeds/m^2 out to 80 m. When extrapolated throughout the burned landscape, estimated seed delivery was low (<49,400 seeds/ha) in >70% of areas that burned in short-interval fire (<30 yr). As fire frequency increases, immaturity risk will be compounded in short-interval fires because seed dispersal from surrounding young trees is limited." (Gill et al.2021) wind dispersal distance* (m): *P. contorta* = 28.0; *P ponderosa* = 25.6; * Calculated from a simple model of ballistic dispersal (Greene and Johnson 1989): wind speed (2.5 m/sec) × release height (10 m) divided by descent velocity. (Vander Wall, 2003) A comparison of the seed dispersal characteristics of nine conifers of the Inland Mountain West. This relates the number of seeds found at the seed source to the numbers found at increasing distances from the source. seeds dispersed (%) at 120 m metres as a percent of seed from seed source: lodgepole < ponderosa < western larch < western hemlock (McCaughey et al.1986) "Lodgepole pine seed is light, averaging about 100,000 seeds per pound, with about 1/3 to 1/2 pound of seed per bushel of cones (Bates 1930). Dispersal from standing trees is largely by wind, but wind is important only in stands where non-serotinous cones are abundant (Tackle 1961a). Seedfall into cleared openings has been studied in Montana and Oregon (Boe 1952, 1956; Dahms 1963, Tackle 1964). Seed dispersed from standing timber dropped off sharply at a distance of about 66 ft and continued to diminish as distance from the source increased. These authors concluded that the number of seeds dispersed beyond 200 ft from the source was inadequate to restock a cutover area regardless of the amount of seed released under the uncut stand. More

Species	Common	Dispersal
		seeds were dispersed from the north and west boundaries than from the south and east boundaries on most areas studied, but differences were too small to detect any influence of prevailing winds on seed dispersal" (Alexander 1974) "It has been assumed that secondary dispersal of winged pine seeds across the ground occurs, but the process has been little studied. We monitored the fates of 287 inedible pine seeds that differed in size (lodgepole pine, *Pinus contorta*, mean fresh seed mass with wing 9 ± 2 mg; ponderosa pine, *P. ponderosa*, 62 ± 11 mg; and Jeffrey pine, *P. jeffreyi*, 185 ± 23 mg) to determine the effects of wind and gravity on secondary dispersal across the ground. Animals largely ignored the seeds. Most seeds moved <1 m during the 37-day observation period. Only seven seeds were known to have moved >1 m. Nineteen seeds disappeared, but rodents and birds probably took many of these. Seeds placed on mineral soil moved significantly farther than those placed on pine needle litter, and, on needle litter, large seeds moved significantly farther than small seeds. Except during an initial windy period, most seeds moved <5 cm/day. Most seeds became immobile after about 8 days because they became entrapped in plant litter. By the end of the study, only two lodgepole pine seeds had become completely buried in soil. Wind and gravity appear to be relatively ineffective at moving pine seeds long distances across the ground surface. For large pine seeds (e.g., those of ponderosa and Jeffrey pine), rodents and birds serve as an alternative means of secondary dispersal by scatter hoarding seeds in soil, whereas small pine seeds (e.g., those of lodgepole pine) are more likely to be overlooked by foragers as they are gradually buried in plant litter and soil." (Vander Wall and Joyner 1998)
Pinus sylvestris	Scots	"Seed dispersal for natural restocking of cutover areas is normally limited to between 50 and 100 m (164 to 328 ft) from the parent tree. Maximum seed dispersal is much greater, however. In northern New York, the establishment of second-generation natural Scotch pine seedlings up to at least 1 km (0.6 mi) from the seed source is the rule rather than the exception." (Burns and Honkala 1990) "Literature in *P. sylvestris* shows that fifty percent of the seeds remain under the crown, while other 40% of the seeds are found at distances as long as 2 to 4 times the tree height (Burschel and Huss, 1997). This means that between 30 and 75% of the seeds are found not more than 18 m from the tree (Montero et al., 2008a). In our specific study area only 20% of the seeds were released under the crown, while in a distance of three crown radii the number of dispersed seeds is similar to that beneath the crown (Calama et al., 2015b), resulting in a close to uniform distribution of the seed rain on the soil surface." (Calama et al.2017) "The recruitment model differed significantly between *P. sylvestris* and *P. nigra*: a general model that assumed equal recruitment parameters for both species had a significantly higher deviance than a model allowing different dispersal parameters (likelihood ratio test, $P < 0.05$). First, the estimated mean dispersal distance of *P. nigra* was longer than the mean dispersal distance of P. sylvestris (Table 2), and the four dispersal kernels show that the dispersal kernels decrease faster for *P. sylvestris* than for *P. nigra* (Fig. 2). The mean dispersal distance was two to three times farther for *P. nigra* than for *P. sylvestris* (Table 2). The density of seedlings predicted at 50 m from an adult tree was more than 10 times higher for *P. nigra* than for *P. sylvestris*." (Debain et al.2007) "The reproductive parameter w that expresses the increase in the probability of a tree being sexually mature with age was higher for *P. sylvestris* than for *P. nigra* (Table 2), and the z parameter, which is related to the

Species	Common	Dispersal
		age of first reproduction, was lower for *P. sylvestris* than for *P. nigra* (Table 2), resulting in a more precocious fecundity for P. sylvestris (Fig. 3a). The net fecundity parameter u was clearly higher in *P. nigra* (Table 2). The latter species becomes sexually mature later but produces more seedlings than *P. sylvestris* (Fig. 3b)" (Debain et al.2007) "Results for the morphological traits of seeds showed significant differences between trees ($p = 0.0001$, Table 3). The tree effect accounted for 22 to 45% of the total variability. These three seed traits were correlated ($0.38 < r < 0.47$, $p < 0.0001$). In addition, we recorded a negative correlation of seed weight ($r = -0.07$, $p = 0.0003$) and length ($r = -0.12$, $p < 0.0001$) with the age of the mother tree." (Pardos et al.2022) The age of mother tree had a significant effect on seed weight (Table 3, Figure 2). As in the previous case, for this trait, we also observed a significant decrease with age, up to a tree age over 150–175 years, when a slight increase in the values was detected." (Pardos et al.2022)
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	"For *P. nigra*, despite uncertainty in parameter estimates, spread is promoted by high LDD probabilities and high dispersal distances. It is therefore particularly important to prioritize removal of plants 'upstream' of vulnerable habitat and particularly from areas where dispersal of propagules is maximized. For P. nigra this means removal of trees where there is a high probability of diaspores being taken up into the air-stream and transported long distances, preferably before these trees become reproductive." (Buckley et al.2005) "Ungrazed grassland environments were most vulnerable to invasion and the highest elasticities and sensitivities of invasion speed were to long-distance dispersal parameters." (Buckley et al.2005) "Wave speeds estimated here are very high, > 1000 m $year^{-1}$; the main reason for this is that the long-distance dispersal parameters were calculated from data in one take-off site, a hill exposed to warm north-westerly winds in the coning season, with vulnerable ungrazed grassland habitat down-wind of the source. The landscape over which the invasion wave moves will change, leading to variable dispersal kernels" Buckley et al.2005) "The recruitment model differed significantly between *P. sylvestris* and *P. nigra*: a general model that assumed equal recruitment parameters for both species had a significantly higher deviance than a model allowing different dispersal parameters (likelihood ratio test, $P < 0.05$). First, the estimated mean dispersal distance of *P. nigra* was longer than the mean dispersal distance of *P. sylvestris* (Table 2), and the four dispersal kernels show that the dispersal kernels decrease faster for *P. sylvestris* than for P. nigra (Fig. 2). The mean dispersal distance was two to three times farther for *P. nigra* than for *P. sylvestris* (Table 2). The density of seedlings predicted at 50 m from an adult tree was more than 10 times higher for *P.* nigra than for *P. sylvestris*." (Debain et al.2007) "The reproductive parameter w that expresses the increase in the probability of a tree being sexually mature with age was higher for *P. sylvestris* than for *P. nigra* (Table 2), and the z parameter, which is related to the age of first reproduction, was lower for *P. sylvestris* than for *P. nigra* (Table 2), resulting in a more precocious fecundity for *P. sylvestris* (Fig. 3a). The net fecundity parameter u was clearly higher in *P. nigra* (Table 2). The

Species	Common	Dispersal
		latter species becomes sexually mature later but produces more seedlings than *P. sylvestris* (Fig. 3b)" (Debain et al.2007)
Pinus ponderosa	Ponderosa	"Ponderosa pine seeds are not disseminated naturally over extensive distances. In central Oregon, seedfall at 37 m (120 ft) was only 22 percent of the seedfall at the west edge of a cleared area, and at 120 m (396 ft) it was only 8 percent." (Burns and Honkala 1990) wind dispersal distance* (m): *P. contorta* = 28.0; *P ponderosa* = 25.6; * Calculated from a simple model of ballistic dispersal (Greene and Johnson 1989): wind speed (2.5 m/sec) × release height (10 m) divided by descent velocity. (Vander Wall, 2003) A comparison of the seed dispersal characteristics of nine conifers of the Inland Mountain West. This relates the number of seeds found at the seed source to the numbers found at increasing distances from the source. seeds dispersed (%) at 120 m metres as a percent of seed from seed source: lodgepole < ponderosa < western larch < western hemlock (McCaughey et al.1986) "It has been assumed that secondary dispersal of winged pine seeds across the ground occurs, but the process has been little studied. We monitored the fates of 287 inedible pine seeds that differed in size (lodgepole pine, *Pinus contorta*, mean fresh seed mass with wing 9 ± 2 mg; ponderosa pine, *P. ponderosa*, 62 ± 11 mg; and Jeffrey pine, *P. jeffreyi*, 185 ± 23 mg) to determine the effects of wind and gravity on secondary dispersal across the ground. Animals largely ignored the seeds. Most seeds moved <1 m during the 37-day observation period. Only seven seeds were known to have moved >1 m. Nineteen seeds disappeared, but rodents and birds probably took many of these. Seeds placed on mineral soil moved significantly farther than those placed on pine needle litter, and, on needle litter, large seeds moved significantly farther than small seeds. Except during an initial windy period, most seeds moved <5 cm/day. Most seeds became immobile after about 8 days because they became entrapped in plant litter. By the end of the study, only two lodgepole pine seeds had become completely buried in soil. Wind and gravity appear to be relatively ineffective at moving pine seeds long distances across the ground surface. For large pine seeds (e.g., those of ponderosa and Jeffrey pine), rodents and birds serve as an alternative means of secondary dispersal by scatter hoarding seeds in soil, whereas small pine seeds (e.g., those of lodgepole pine) are more likely to be overlooked by foragers as they are gradually buried in plant litter and soil." (Vander Wall and Joyner 1998) "The proportion (%) of seed of each species that fell within an area Ph times the height of the average dominant tree (200 feet) was: Species Douglas-fir 98 White fir 91 Ponderosa pine 89 Incense-cedar 100" (McDonald 1980)

Species	Common	Dispersal
Pinus muricata	bishop	
Pinus pinaster	maritime	"The best-fitting seed dispersal kernels can be classified in three groups according to kernel shape (Fig. 3), with models built for Cu04, Cu05 and Co00 showing intermediate seed dispersal probability functions (Table 4). Log-normal kernels for Cu06 and Cu07 have slightly higher shape parameters, which thickens the far tail while pushing the modal density backwards towards the mother tree. In contrast, 2Dt kernels for Coca in the same years (Co06 and Co07) have large scale parameters and extended far tails (Table 4). Median dispersal distances varied from 14.10 m in Co00 to a maximum of 24.53 m in Cu05, with an average across years and sites of 20.29 ± 3.97 m. Median dispersal distances varied notably among dates within dispersal seasons, for example from 9.96 to 32.37 m in Cu04 and from 12.24 to 54.91 m in Cu05 (Fig. 4). Among the fitted intraseasonal kernels in Cuéllar, the one corresponding to 18th June 2005 stands out because of its largest fecundity (i.e. seeds available for dispersal) and median dispersal distances, 6574 and 54.91 m, respectively." (Juez et al.2014)
Pinus radiata	Monterey	
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	"Although reports of fully stocked stands resulting from seedfall from sources 1 to 2 km (0.6 to 1.2 mi) distant are not rare, the great majority of Douglas-fir seeds fall within 100 m (330 ft) of a seed tree or stand edge." (Burns and Honkala 1990) "The proportion (%) of seed of each species that fell within an area Ph times the height of the average dominant tree (200 feet) was: Douglas-fir 98 White fir 91 Ponderosa pine 89 Incense-cedar 100" (McDonald 1980) The quantity of seed that fell to the ground decreased rapidly from the timber edge up to about four chains for Douglas-fir and six chains for larch (figure l) o Beyond these distances the quantity remained fairly constant at a low level to the farthest sampling point 12 chains (792 feet) from the source o An average of only 5,227 Douglas-fir seeds and 15,682 larch seeds per acre were scattered beyond the four- and six-chain distances, respectively o these average quantities are only three percent of the Douglas-fir and five percent of the larch seed dispersed in the uncut timber during the excellent 1952 seed year" (Boe 1953) "The greatest quantities of larch seed were dispersed from the westerly sides of the cuttings (figure 1). The amount scattered from the north-west (downhill) side was significantly greater than from the northeast

Species	Common	Dispersal
		(downhill) and southeast (uphill) sides and exceeded that from the southwest (uphill) side. The dispersal pattern for Douglas-fir was similar to that for larch. " (Boe 1953)
Larix decidua	European larch	
Larix laricina	tamarack	"Although the seeds are small, few fall at a distance greater than twice the tree height. However, tamarack can reproduce well as far as 60 m (200 ft) from seed-bearing trees if favorable seedbeds are present" (Burns and Honkala 1990) The relationship of seedfall (filled seed) to distance from the nearest seed source was described, however, by the following equation (Fig.4): [1] log10 (filled seed/m2 + 1) = -0.96 (log10(distance (m) + 1) + 2.61 (n=30, r= -0.64, P = 0.0001). (Brown et al.1988) [Note: this roughly translates to 140.89 seeds/m² at 2m, 1.51 seeds/m² at 200m, and -0.72 seeds/m² at 2000m. MBS] "This relationship predicts that the density of filled seed landing 9m (1 tree height) from the nearest tree is only 11% of that landing under the tree and the density of filled seed landing 18m from the nearest tree is approximately 6% of that landing under the tree" (Brown et al.1988)
Larix occidentalis	western larch	A comparison of the seed dispersal characteristics of nine conifers of the Inland Mountain West. This relates the number of seeds found at the seed source to the numbers found at increasing distances from the source. seeds dispersed (%) at 120 m metres as a percent of seed from seed source: lodgepole < ponderosa < western larch < western hemlock (McCaughey et al.1986) The quantity of seed that fell to the ground decreased rapidly from the timber edge up to about four chains for Douglas-fir and six chains for larch (figure 1). Beyond these distances, the quantity remained fairly constant at a low level to the farthest sampling point 12 chains (792 feet) from the source. An average of only 5,227 Douglas--fir seeds and 15,682 larch seeds per acre were scattered beyond the four- and six-chain distances, respectively. These average quantities are only three percent of the Douglas-fir and five percent of the larch seed dispersed in the uncut timber during the excellent 1952 seed year" (Boe 1953) "The greatest quantities of larch seed were dispersed from the westerly sides of the cuttings (figure 1). The amount scattered from the north-west (downhill) side was significantly greater than from the northeast (downhill) and southeast (uphill) sides and exceeded that from the south-west (uphill) side. The dispersal pattern for Douglas-fir was similar to that for larch." (Boe 1953)
Sequoia sempervirens	Coastal redwood	"Redwood seeds are small and light, number about 265,000kg (120,000/lb), but lack efficient wings to slow them in falling. They fall at rates between 1.5 and 6.2 m/s (4.9 and 20.5 ft./s), averaging 2.6 m/s (8.6 ft/s). These rates are faster than for most other wind-disseminated forest seeds and limit seed dispersal considerably." (Burns and Honkala 1990) "Timbered edges of clearcut units have effective seeding distances of only 61 m (200 ft) uphill and 122 m (400 ft.) downhill under average redwood stand conditions. A recent study in Del Norte County, CA, showed that the largest clearcut units should not be more than 12 to 16 ha (30 to 40 acres) if regeneration will be completed by natural seeding " (Burns and Honkala 1990)

Species	Common	Dispersal
		At 396 feet (120.7m) 196 sound seed per acre (79.3 / ha) Boe 1961
Sequoiadendron giganteum	Giant redwood	
Picea abies	Norway spruce	"Depending on tree height and fecundity, the peak seed deposition from any reproducing tree occurred between 0.5 m and 2.1 m from that tree (i.e., directly under its crown) and rapidly decreased with distance to produce short mean dispersal distances between 4.3 m and 17.4 m (Fig. 3). The seed dispersal model produced a good fit between the observed (O) and predicted (E) seed rain densities (r = 0.77, O = -3.92 + 1.02 * E), predicted seed rain was unbiased (t-test: intercept = 0, t = -0.115, P < 0.91), and the relationship between the observed and predicted seed rain was that of identity (t-test: slope = 1, t = -0.131, P < 0.90). The model performed equally well across the invasion gradient, as the regression residuals did not correlate with the distance to the forest edge (r = 0.19, P < 0.21)." (Dovčiak et al.2008)
Picea engelmannii	Engelmann spruce	*Picea engelmannii*: "A mathematical expression was developed to estimate *Picea engelmannii* seed dispersal into clearcut openings. The pattern of seed dispersal is a rapid decline from within the windward stand to the stand edge and beyond into the opening. Amount of seedfall dispersed to the windward stand edge is c.80% of the seedfall under the uncut, windward stand. About 40% of the seedfall under the uncut stand is dispersed as far as 100 ft into the opening, and 10% as far as 300 ft. The initial rapid decline is followed by a gradual leveling-off, with 1% of the amount of seedfall under uncut stands dispersed as far as 600 ft." (Alexander and Edminster 1983) "Nonlinear least squares regression program was then used to fit the data to the following model: SD = SO exp[- b1(D + 33)b2) [1) where SD = Number of sound seeds per acre falling at distance D into the openings (the windward stand edge is denoted by D = O) SO = Number of sound seeds per acre falling under the uncut stand 33 feet from the windward stand edge (denoted by D = -33)2 D = Distance in feet into the opening from windward stand edge bt, bz = coefficients. The estimated value of b2 was nearly 1.0; therefore, the following simplified model was then fit: SD = SO exp[- b1(D + 33)]. The residual sums of squares of the two models were nearly equal. The resulting equation from the single coefficient model is: SD = SO exp(- 0.00735D - 0.243) [3] R2 = 0.99, Sy:x = 37,500 sound seeds per acre. Although the equation accounts for 99% of the variability centered about the mean, the high standard error of estimate indicates that a large amount of variability is not accounted for by the equation. " (Alexander and Edminster 1983) "Estimates of seedfall into openings generally follows the pattern previously described for the Rocky Mountains. The amount of seedfall dispersed to the windward stand edge is about SOO/o of the seedfall under the uncut stand. About 40% of the amount of seedfall under the uncut windward stand is dispersed as far as 100 feet, and about 10% as far as 300 feet. The rapid decline in seedfall then levels off, with about 1% of the amount of seed falling under uncut stands dispersed as far as 600 feet from the windward stand edge. This is in general agreement with the 0.5% to 5% estimates of seedfall at 600 feet from source observed by Roe (1967). There are two important differences, however. Equation [3) is based on estimates of sound seed, not total seedfall, and on two 1D-year periods of observation." (Alexander and Edminster 1983)

Species	Common	Dispersal
		"Based on the seed dispersal data in table 1, and assuming that, over a 5-year period, the accumulative seed production under uncut windward stands will be at least 1,000,000 sound seeds, the effective seeding distance on scarified-shaded seedbeds on north aspects is about 350 feet from the windward stand edge. Openings 400 to 450 feet wide (assuming an effective seeding distance of 50 to 100 feet from the leeward stand edge) should adequately restock within 5 years. The effective seeding distance on scarified unshaded and unscarified-shaded seedbeds on the north aspect is about 250 feet from the windward stand edge, with openings 300 to 350 feet wide restocking adequately within 5 years. On unscarified unshaded seedbeds on the north aspect, and all seedbeds on the south slope, the effective seeding distance is so limited that clearcutting, with [sic: "out"] adequate natural restocking in a reasonable period of time, is not a viable option." (Alexander and Edminster 1983)
Picea sitchensis	Sitka spruce	"Dispersal distance depends on several factors, including height and location of the seed source, local topography, and wind conditions. Reported dispersal distances range from 0.8 km (0.5 mi) when a seed source was on high ground, to 30 m (100 ft) when seed was released from the edge of a clearcut area (15)" (Burns and Honkala 1990)
Abies grandis	grand fir	"Seeds are dispersed by the wind and rodents." (Burns and Honkala 1990) "Seeds sufficient to produce adequate reproduction may be distributed up to 120 m (400 ft) from the parent tree, but the average distance is about 45 to 60 m (150 to 200 ft)." (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Despite having small wings along both sides, the seeds apparently fall more rapidly than many larger conifer seeds. The seed wings appear to aid their flotation on water" (Burns and Honkala 1990)
Thuja plicata	western red cedar	"They fall faster and do not fly as far as the seeds of western hemlock, Sitka spruce, and Douglas-fir, but. dissemination is adequate within 100 m (330 R) of a seed source" (Burns and Honkala 1990)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S11. Palatability

Species	Common	Palatability
Pinus contorta	lodgepole	"Grazing animals, particularly cattle, can cause seedling mortality by trampling. Sheep actually seek the succulent new “candles” in the spring and nibble needles and small branches if other feed is not abundant."(Burns and Honkala 1990) "1 sheep to 2 acres = 15% survival, 0% healthy seedling survival; 1 sheep to 4 acres = 20% survival, 1.5% healthy seedling survival; 1 sheep to 8 acres = 58% survival, 15% healthy seedling survival; ungrazed 94% survival, 63% healthy seedling survival" (Beneke 1967) "are difficult to kill by grazing after they are 2 years of age; older trees will only be severely hedged by grazing." (Ledgard 2001) Corsican = Douglas fir < European larch < Ponderosa < Scots = Lodgepole; Lodgepole = Radiata. (Crozier and Ledgard 1990) "Beside the herbivory intensity, the severity of damage and thus the potential of large herbivores to control conifer invasion will also depend on the palatability of the species. In this case, P. contorta is considered one of the most preferred species by sheep, among Pinaceae such as *P. radiata*, *P. sylvestris*, *P. ponderosa* and *P. nigra*, (Crozier and Ledgard 1990). So, future activities of management of conifer invasion with herbivory should consider this possible differences in palatability" (Zamora Nasca et al.2018) "Model, Coefficient, Estimate, SE, z value, Pr(>|z|), Probability, 95% CI Lower/Upper Browsing incidence Intercept 0.76 0.65 1.17 0.2412 0.68 0.32 0.91 *P. jefreyi* 0.89 0.38 2.37 0.0179 0.84 0.53 0.96 *P. ponderosa* −0.43 0.35 −1.22 0.2215 0.58 0.23 0.86 *P. radiata* −1.67 0.36 −4.61 3.95E−06 0.29 0.08 0.64 Relative reduction in seedling height Intercept −0.99 0.18 −5.39 7.20E−08 0.27 0.20 0.35 *P. jefreyi* −0.53 0.17 −3.13 0.0018 0.18 0.13 0.24 *P. ponderosa* −0.15 0.17 −0.85 0.3957 0.24 0.18 0.31 *P. radiata* −0.2 0.17 −1.17 0.2432 0.23 0.17 0.3 Probability of terminal bud damage Intercept −0.24 0.49 −0.48 0.628751 0.44 0.2 0.71 *P. jefreyi* −1.22 0.34 −3.62 0.000291 0.19 0.06 0.42 *P. ponderosa* −0.65 0.32 −2.04 0.041353 0.29 0.11 0.56 *P. radiata* −0.54 0.32 −1.71 0.087385 0.31 0.12 0.59 Browsing intensity

Species	Common	Palatability
		Intercept −0.92 0.46 −1.99 0.0466 0.28 0.11 0.54 *P. jefreyi* −0.6 0.14 −4.14 3.45E−05 0.18 0.07 0.4 *P. ponderosa* 0.01 0.18 0.05 0.9566 0.29 0.11 0.55 *P. radiata* −0.07 0.24 −0.27 0.7846 0.27 0.1 0.54 Probability of defoliation Intercept −2.15 0.44 −4.93 8.18E−07 0.1 0.04 0.22 *P. jefreyi* 2.41 0.39 6.25 4.23E−10 0.56 0.36 0.75 *P. ponderosa* 1.31 0.39 3.41 0.000656 0.3 0.15 0.5 *P. radiata* −1.91 0.78 −2.45 0.014239 0.017 0.002 0.06 Probability of survival Intercept 2.53 0.52 4.84 1.30E−06 0.93 0.81 0.98 *P. jefreyi* 2.31 1.05 2.21 0.0274 0.99 0.96 1 *P. ponderosa* −0.33 0.47 −0.71 0.4753 0.9 0.76 0.97 *P. radiata* −0.16 0.48 −0.33 0.74 0.91 0.79 0.98; Table 1. Results of the models performed to analyze sheep herbivory preference between four invasive pine species. We present the estimated value (Logit scale), standard error, z-value and their associated p value, and probability and lower and upper limits of the 95% confidence interval. Significant p values are highlighted in bold." (Zamora Nasca et al.2020) "In general terms, the browsing incidence on *P. contorta*, *P. ponderosa*, *P. radiata*, and *P. jefreyi* seedlings, as estimated by the model, was 68%, 58%, 29%, and 84% respectively (Table 1). *Pinus radiata* seedlings were significantly less browsed than the seedlings of the other three pine species, while *P. jefreyi* seedlings were significantly more browsed than the seedlings of the other species (Fig. 1a, results of post-hoc comparisons can be found as Supplementary Table S2.1 online). The relative reduction in *P. contorta*, *P. ponderosa*, *P. radiata*, and *P. jefreyi* seedling height estimated by the model was 27%, 24%, 23%, and 18% respectively (Table 1) with the reduction in height of *P. contorta* seedlings significantly higher than the reductions in height of *P. radiata* and *P. jefreyi* seedlings; and reductions in height of *P. ponderosa* seedlings were significantly greater than the reduction in height of *P. jefreyi* seedlings (Fig. 1b; results of post-hoc comparisons can be found as Supplementary Table S2.1 online). The probability that a terminal bud of a *P. contorta*, a *P. ponderosa*, a *P. radiata* and a *P. jefreyi* seedling being damaged, as estimated by the model, was 44%, 29%, 31%, and 19% respectively (Table 1); with the proportion of terminal bud browsed of *P. contorta* seedlings significantly higher than the proportion of terminal bud browsed of *P. jefreyi* (Fig. 1c, results of post-hoc comparisons can be found as Supplementary Table S2.1 online). The browsing intensity of *P. contorta*, *P. ponderosa*, *P. radiata* and *P. jefreyi* seedlings estimated by the model was 28%, 29%, 27%, and 18%, respectively (Table 1); with the browsing intensity of *P. jefreyi* significantly lower than the browsing intensity of *P. contorta* and *P. ponderosa* (Fig. 1d, results of post-hoc comparisons can be found as Supplementary Table

Species	Common	Palatability
		S2.1 online). In terms of the probability of a seedling having only the needles damaged, i.e., being defoliated, the probability estimated by the model for *P. contorta*, *P. ponderosa*, *P. radiata* and *P. jefreyi* seedling was 10%, 30%, 1.7%, and 56% respectively (Table 1). These percentages differed significantly for the four species (Fig. 1e, results of post-hoc comparisons can be found as Supplementary Table S2.1 online). The probability of survival of a *P. contorta*, a *P. ponderosa*, a *P. radiata* and a *P. jefreyi* seedling immediately after the treatment was 93%, 90%, 91% and 99% respectively (Table 1), with the probability of survival of *P. jefreyi* significantly higher than the probability of survival of *P. ponderosa* and *P. radiata* seedlings (Fig. 1f; results of post-hoc comparisons can be found as Supplementary Table S2.1 online)" (Zamora Nasca et al.2020) Grazing: regrowth unless all live/green foliage has been removed in grazing; reasonably palatable to sheep (Timmins and Mackenzie 1995)
Pinus sylvestris	Scots	Corsican = Douglas fir < European larch < Ponderosa < Scots = Lodgepole; Lodgepole = Radiata. (Crozier and Ledgard 1990) "This study analyses the impact of herbivory in a Mediterranean treeline of widespread *Pinus sylvestris* and *P. nigra* pinewoods, testing whether herbivory damage reinforces or inhibits the climatic responses of these trees. We used naturally occurring sapling pairs of similar size and age of both species, thereby isolating plant characteristics from environmental effects in herbivore behaviour. Herbivory damage by ungulates proved higher than that caused by insects in saplings of both species. Low plant density and extreme abiotic conditions at the treeline could in part be responsible for the observed low incidence of insect herbivory. Ungulates preferred *P. sylvestris* over *P. nigra*, implying heavier browsing damage for a large number of *P. sylvestris* saplings, suffering reduced internode growth as a consequence. In addition, *P. sylvestris* could not compensate height-growth reductions due to browsing with higher growth rate than *P. nigra*. In fact, *P. sylvestris* showed similar or lower relative height growth with respect to *P. nigra*. Under a scenario of increasing aridity and maintenance of ungulate populations, the upward migration of *P. sylvestris* in its southern range could be restricted by higher drought vulnerability than *P. nigra*, a situation exacerbated by ungulate herbivory. Our results indicate that ungulate herbivory reinforces climatic response of coexisting *P. sylvestris* and *P. nigra* at treeline, favouring a potential change in community dominance towards Mediterranean *P. nigra*" (This study analyses the impact of herbivory in a Mediterranean treeline of widespread *Pinus sylvestris* and *P. nigra* pinewoods, testing whether herbivory damage reinforces or inhibits the climatic responses of these trees. We used naturally occurring sapling pairs of similar size and age of both species, thereby isolating plant characteristics from environmental effects in herbivore behaviour. Herbivory damage by ungulates proved higher than that caused by insects in saplings of both species. Low plant density and extreme abiotic conditions at the treeline could in part be responsible for the observed low incidence of insect herbivory. Ungulates preferred *P. sylvestris* over *P. nigra*, implying heavier browsing damage for a large number of *P. sylvestris* saplings, suffering reduced internode growth as a consequence. In addition, *P. sylvestris* could not compensate height-growth reductions due to browsing with higher growth rate than *P. nigra*. In fact, *P. sylvestris* showed similar or lower relative height growth with respect to *P. nigra*. Under a scenario of increasing aridity and maintenance of ungulate populations, the upward migration of *P. sylvestris* in its southern range could be restricted by higher drought vulnerability than *P. nigra*, a situation exacerbated by

Species	Common	Palatability
		ungulate herbivory. Our results indicate that ungulate herbivory reinforces climatic response of coexisting *P. sylvestris* and *P. nigra* at treeline, favouring a potential change in community dominance towards Mediterranean *P. nigra*. (Herrero et al.2012) "*P. sylvestris* presented a significantly higher risk of herbivory than *P. nigra* (Fig. 2), for both accumulated (X^2 = 18.66, P< 0.0001) and annual herbivory (X^2 = 32.58, P < 0.0001). In addition, significant differences were recorded between the sites for accumulated (X^2 = 9.47, P = 0.0088) and annual herbivory (X^2 = 7.11, P = 0.0286; Fig. 2). Accumulated and annual damage intensity was higher for *P. sylvestris* than for *P. nigra* in all the cases, as was leader browsing (Tables 2, 3; Fig. 2). There were differences amongst sites, as reported by the significant site factor and site 9 species interaction. Nevertheless, in all the cases the differences amongst two pines were clear, with *P. sylvestris* showing consistently higher and often much higher damage than *P. nigra* (Tables 2, 3; Fig. 2). Internode growth of the last 4 years standardized by internode age differed between browsed and unbrowsed saplings, pooling individuals of the three sites (F = 12.98, P = 0.0005 and F = 35.31, P\0.001 for *P. sylvestris* and *P. nigra* saplings, respectively; Fig. 3). In addition, significant differences were found between different years (F = 2.72, P = 0.0494 and F = 4.39, P = 0.0064, respectively)." (Herrero et al.2012) "Insect herbivory: The percentage of saplings affected by *Rhyacionia duplana* and *T. pityocampa* was very low for both species (Table 4). Although the incidence of herbivory by *Retinia resiniella* (only for *P. sylvestris*) and leaf feeders was considerable, both the number of galls and the percentage of damaged needles per sapling were rather low (Table 4)" (Herrero et al.2012) "It is clear from our results that ungulates preferred *P. sylvestris* over *P. nigra*, in agreement to previous studies in the area (Baraza et al. 2009). This preference involves higher browsing damage for large number of *P. sylvestris* saplings, which consequently suffered a reduction in height growth, and therefore an increase in pine saplings risk of herbivore damage." (Herrero et al.2012)
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	"Newly germinated seedlings suffered very heavy losses from voles and rabbits but became unpalatable to them within 2 months." (Burns and Honkala 1990) Grazing: most unpalatable conifer in high-country; regrowth will occur unless all green foliage is removed in grazing (Timmins and Mackenzie 1995)
Pinus ponderosa	Ponderosa	"Rabbits and hares injure or kill many seedlings, and pocket gophers are especially destructive. In areas where pocket gopher populations are high all seedlings and many saplings may be destroyed. Squirrels and porcupines attack sapling and pole-size trees and, although rarely killing them, deform the stems on which they feed. Repeated browsing by deer has stunted seedlings for 50 years or more. In the absence of regulation, sheep and cattle have damaged reproduction by trampling, bedding, and occasional browsing." (Burns and Honkala 1990) Corsican = Douglas fir < European larch < Ponderosa < Scots = Lodgepole; Lodgepole = Radiata. (Crozier and Ledgard 1990)

Species	Common	Palatability
		"There was no mortality in the species tested, other than radiata and ponderosa pines (Fig. 2). Ponderosa pine had the highest level of mortality after the intensive grazing (12.5%), but few seedlings died throughout the rest of the grazing period. Conversely, the mortality of radiata pine was insignificant initially but rose to 34% by the final assessment. " (Crozier and Ledgard 1990)
Pinus muricata	bishop	
Pinus pinaster	maritime	Grazing: regrowth expected unless all green foliage is removed in grazing (Timmins and Mackenzie 1995)
Pinus radiata	Monterey	Corsican = Douglas fir < European larch < Ponderosa < Scots = Lodgepole; Lodgepole = Radiata. (Crozier and Ledgard 1990) "There was no mortality in the species tested, other than radiata and ponderosa pines (Fig. 2). Ponderosa pine had the highest level of mortality after the intensive grazing (12.5%), but few seedlings died throughout the rest of the grazing period. Conversely, the mortality of radiata pine was insignificant initially but rose to 34% by the final assessment. " (Crozier and Ledgard 1990) "Grazing: relatively palatable conifer, but can regrow if green foliage remains " (Timmins and Mackenzie 1995)
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	Corsican = Douglas fir < European larch < Ponderosa < Scots = Lodgepole; Lodgepole = Radiata. (Crozier and Ledgard 1990) "Grazing: unpalatable to sheep browsing but recovers well from browsing damage" (Timmins and Mackenzie 1995)
Larix decidua	European larch	Corsican = Douglas fir < European larch < Ponderosa < Scots = Lodegpole; Lodgepole = Radiata. (Crozier and Ledgard 1990) Conifer needles comprise the winter diet of these tetraonids. Tamarack (*Larix laricina*) needles are the preferred food of spruce grouse (98) and blue grouse (20) in western North America. Larch (*L. occidentalis*) needles are preferred by spruce grouse in eastern North America (30). After *Larix* shed their needles in early winter, pine (*Pinus*) becomes the preferred food of both spruce grouse and blue grouse. Blue grouse (20) and spruce grouse (98, 154-156) feed preferentially upon lodgepole pine (*P. contorta*) in western North America, and in eastern North America spruce grouse feed preferentially upon the jack pine (*P. banksiana*) (30, 69). The capercaillie feeds preferentially upon *Larix* (R. Moss, personal communication) and Scots pine (*P. sylvestris*) (115, 162, 182). Fir (*Abies*) is less palatable to spruce grouse than pine (98, 154, 192). Spruce (*Picea*) is the least palatable conifer to all three species during midwinter (20, 30, 98, 115, 154, 182). In North America white spruce (*P. glauca*) is considerably more palatable to spruce grouse than black spruce (*P. mariana*) (41, 42). During spring, however, expanding foliar buds of spruce are the preferred and predominant food of spruce grouse (80)" (Bryant and Kuropat 1980)

Species	Common	Palatability
		"Forage preferences of snowshoe hares and mountain hares are willow > aspen > larch > dwarf birch > tree birch > pine (jack pine = lodgepole pine = scots pine > white pine > red pine) > fir > spruce (white spruce > black spruce) > alder (e.g. 3, 12, 22, 25, 28, 36, 38, 48, 104, 113, 114, 183, 184, 201). " (Bryant and Kuropat 1980)
Larix laricina	tamarack	"*Larix laricina* is more palatable to the snowshoe hare, *Lepus amaericanus* (Bryant and Kuropat 1980), than is *Picea glauca*, and may therefore be subject to more grazing pressure." (Brown et al.1988)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	"Woodrats often injure planted trees on cutover land and occasionally attack sprouts and larger trees." (Burns and Honkala 1990)
Sequoiadendron giganteum	Giant redwood	
Picea abies	Norway spruce	"In the five main species categories (*Abies*, *Picea*, *Acer*, *Fagus* and *Fraxinus*), the average seedling density was between 0.30 and 0.94 seedlings per m^2. *Acer* seedlings had the highest density in a single plot (159 seedlings per m^2) and *Sorbus* seedlings the lowest, with a mean of 0.09 seedlings per m^2 and a maximum density of 7.9 seedlings per m^2 (Table 3). Despite the requirement for a minimum number of firs in each IA (see methods section), the PBs varied widely; for example, the *Abies alba* PB ranged from 4 to 98% (Fig. 1). However, for no species was there a clear association between PB and seedling density, neither at the IA level nor at the species:year:hc:IA:plot level (Fig. 1)." (Kupferschmid et al.2019) "An experiment with saplings from 90 *Abies alba* and 72 *Picea abies* seed sources was conducted. Five-year-old saplings were clipped at three intensities before budburst in spring. Growth (height, diameter, leader shoot length, and biomass) and quality (e.g. stem form, multistemming, reaction type) were assessed before and 1–2 years after clipping or 3–4 years after natural frost events, and provenance differences were related to environmental differences at the seed source. For *Abies*, frost and clipping resulted in reduced height growth in the first year after the stress and reduced height for two (clipping) to four (frost) vegetation periods. Sapling biomass, diameter increment, and quality decreased after heavy clipping. For *Picea*, which grew twice as fast as *Abies*, such effects were only found after frost damage." (Kupferschmid and Heiri 2019) "Lightly browsed *Abies* saplings grew better than those that were not browsed, which in turn grew better than strongly browsed saplings. This pattern, which occurred irrespective of forest type, was caused by selective browsing on vigorously growing trees and led to a greater impact of strong browsing in comparison to light browsing on the growth of *Abies* saplings. The ratio of the relative growth rate of *Abies* to *Picea* was altered by within-tree browsing intensity, forest type and soil depth. Generally, this ratio was highest in shallow soiled *Fagus*-dominated forests after light browsing and lowest in *Fagus-Abies* forests after strong leader shoot browsing, indicating a browsing-induced shift in the relative difference in growth rate between species towards *Picea* in *Fagus-Abies* and *Picea-Abies* forests but not in *Fagus*-dominated forests." (Kupferschmid 2018)

Species	Common	Palatability
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	
Thuja plicata	western red cedar	"Redcedar seedlings and saplings are often severely browsed by deer, elk, or rodents, and browse damage may be the most important stand-establishment problem." (Burns and Honkala 1990)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S12. Shade tolerance

Species	Common	Shade tolerance
Pinus contorta	lodgepole	"Lodgepole is very intolerant of shade and generally grows best in full sunlight." (Burns and Honkala 1990) "Lodgepole pine is very intolerant of shade and competition from other plant species. Occasionally seedlings become established under a forest canopy, but these individuals rarely do well." (Burns and Honkala 1990) "Intolerant (establishment), tolerant to partial shade" (Timmins and Mackenzie 1995) "balsam fir = subalpine fir > white spruce = interior spruce > lodgepole pine = jack pine" (Claveau 2002) "Effect of competition on tree survival are related to both shade-tolerance of the species and stand composition. Shade intolerant pine species (lodgepole and jack) are strongly and negatively affected by competition from overtopping (larger) trees of all tree species (i.e. spruce/fir, deciduous and pine groups). Other studies also indicate high levels of mortality for shade-intolerant species that are more affected by overtopping competition than shade-tolerant species (e.g. Temesgen and Mitchell, 2005)." (Cortini et al.2017) shade intolerant (won't establish in a dense forest), tolerant to partial shade (Timmins and Mackenzie 1995)
Pinus sylvestris	Scots	"Scotch pine, like many of the hard pines, is intolerant of shade." (Burns and Honkala 1990) European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason 2004) Intolerant but can grow in shaded conditions (less efficient) (Gaudio 2011) *P. pinaster* < *P. sylvestris* < *P. nigra* (Calama et al.2017) Examination of differential species survival from the W to the N treatments suggests a ranking in terms of increasing shade tolerance as European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason et al.2004)
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	Intolerant (slow starting/light demander) (Timmins and Mackenzie 1995) *Pinus nigra* < Douglas fir (Davis 2011) "European black pine is classed as intolerant of shade, and, therefore, must be planted in situations where it will receive full sunlight." (Burns and Honkala 1990) *P. pinaster* < *P. sylvestris* < *P. nigra* (Calama et al.2017) Shade: intolerant-slow starting, light demander (Timmins and Mackenzie 1995)
Pinus ponderosa	Ponderosa	"Even beneath a light overstory stand casting 47 percent shade, ponderosa pine saplings grew only about half as rapidly as their associates (Douglas-fir, sugar pine, white fir, and incense-cedar) and about half of that expected for fully lighted pines. Relative to associates elsewhere within its range, ponderosa pine is more shade tolerant than western larch but less tolerant than grand fir and western white pine. Overall, it is most accurately classed as intolerant of shade." (Burns and Honkala 1990)

Species	Common	Shade tolerance
		"Mean survival and its response to %FS [full sun] varied among species (Fig. 1). Survival for Engelmann spruce and Douglas-fir was not significantly related to %FS whereas for ponderosa pine, it significantly decreased with decreasing %FS. At the end of the first growing season, both Engelmann spruce and Douglas-fir had almost 100% survival at all light conditions (Fig. 1A) whereas survival for ponderosa pine significantly declined with decreasing %FS ($\chi^2 = 35.7$, $P < 0.001$). At the end of the second growing season (Fig. 1B), mean accumulated survival for ponderosa pine (79.3%) was significantly lower than that for Douglas-fir and Engelmann spruce (95.5 and 97.6%, respectively) ($\chi^2 = 136.0$, $P < 0.001$). With decreasing %FS, this survival for ponderosa pine significantly decreased ($\chi^2 = 84.4$, $P < 0.001$) whereas for Douglas-fir and Engelmann spruce, survival was independent of %FS ($\chi^2 = 4.12$, $P = 0.90$ for Douglas-fir and $\chi^2 = 12.4$, $P = 0.19$ for Engelmann spruce). At the end of the third growing season, mean accumulated survival significantly differed among species ($\chi^2 = 180.1$, $P < 0.001$). This survival was 63.9, 80.6, and 96.2% for ponderosa pine, Douglas-fir, and Engelmann spruce, respectively. It significantly decreased from intermediate to low %FS for ponderosa pine (Fig. 1C) ($\chi^2 = 48.1$, $P < 0.001$) whereas it did not significantly differ among different levels of %FS for both Douglas-fir and Engelmann spruce ($\chi^2 = 7.19$, $P = 0.62$ and $\chi^2 = 11.3$, $P = 0.27$, respectively)." (Chen 1997)
Pinus muricata	bishop	
Pinus pinaster	maritime	Intolerant (establishment), tolerant to partial shade (Timmins and Mackenzie 1995) *P. pinaster* < *P. sylvestris* < *P. nigra* (Calama et al.2017) shade: tolerant of partial shade, intolerant of dense shade for establishment (Timmins and Mackenzie 1995)
Pinus radiata	Monterey	"Monterey pine exists both as an overstory and an understory tree, it is classed as intermediate in tolerance to shade -- that is, at least as tolerant as any other pine in western North America. Age and site quality, however, affect this assessment. As a sapling or seedling, the species tolerates shade but becomes less tolerant in the pole stage and is intolerant when mature. When overtopped, young pines can withstand a considerable amount of suppression, struggling along for 30 years or more before they die." (Burns and Honkala 1990) Intolerant (Timmins and Mackenzie 1995) Intermediate shade-intolerant (Gibson II 2022) Shade intolerant (Gomez 2019) Shade: intolerant (Timmins and Mackenzie 1995) "In this study, we have tested the hypothesis that forest invasibility can be predicted by the interplay between canopy cover (a proxy of disturbance) and resident species diversity (a proxy of competition intensity) [8]. Our results indicate that canopy cover is sufficient to determine forest invasibility. As this variable is a proxy of light availability, it is the ultimate abiotic driver influencing pine regeneration. We did not detect direct effects of the native plant community on pine regeneration, suggesting no biotic resistance (competition) of the resident community. This result is of major importance because indicates that there are no biotic filters for the colonization and establishment of this invasive tree." (Gómez et al.2019)

Species	Common	Shade tolerance
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	"First-year seedlings survive and grow best under light shade, especially on southerly exposures, but older seedlings require full sunlight." (Burns and Honkala 1990) "Except in its youth, when it is reasonably tolerant of shade, coastal Douglas-fir is classed as intermediate in overall shade tolerance, below most of its common associates in tolerance to shade." (Burns and Honkala 1990) *Pinus ponderosa* < Douglas fir (Burns and Honkala 1990) Tolerant more than other conifers (Timmins and Mackenzie 1995) European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason 2004) *Pinus nigra* < Douglas fir (Davis 2011) Douglas fir < Western hemlock (Mailly 1997) "moderately shade tolerant" (Weston 1957) "The hypothesis tested in this study was that Douglas fir, because of its greater shade tolerance, should establish more successfully than Corsican pine under shaded conditions among kānuka and mānuka communities. The highly significant interaction between seedling survival and canopy cover, with greater survival of Douglas fir in shaded positions, and contrasting greater survival of Corsican pine in the open, provides strong support for the hypothesis. The stronger negative relationships between both seedling number and seedling survival and LAI in Corsican pine than Douglas fir further supports the hypothesis. In contrast to Douglas fir, most of the variation in survival of Corsican pine seedlings was explained by overstorey LAI. These relationships confirm that Douglas fir seedlings are less dependent on a high light environment for establishment than Corsican pine seedlings, and may establish more readily under shaded conditions present in shrubland" (Davis et al.2011) "The present findings are consistent with results of two recent studies that have compared establishment of Douglas fir with pine seedlings in indigenous shrub and tree communities in the Waimakariri Valley. Cattaneo (2002) found that Douglas fir seedlings established close to plants in subcanopy and canopy tiers in shrubland dominated by *Dracophyllum* sp., while lodgepole pine showed no preference for establishing close to plants in the canopy tier of shrubland dominated by *Chionochloa macra* and *Ozothamnus leptophylla*. Cattaneo (2002) considered the improved establishment of Douglas fir seedlings close to shrubs may have been due to the light shade and protection from frosts and desiccation provided by shrub vegetation. Few Douglas fir seedlings established in the open inter-shrub vegetation; in contrast a third of the lodgepole pine seedlings were found in the open. This differed from our study where, although the difference in survival between the two species in favour of Corsican pine was greatest at open sites, Douglas fir seedlings were still present in reasonable numbers in open sites three growing seasons after sowing. More recently, from a study of seedling growth under different forest species, Dehlin et al. (2008) suggested Douglas fir was more shade tolerant than lodgepole pine. They transplanted seedlings of lodgepole pine, Douglas fir and mountain beech (*Nothofagus*

Species	Common	Shade tolerance
		*solandr*i var. *cliffortioides*) into stands of each of these species that differed in light transmission and soil properties. Seedlings of all species had low survival and lost biomass under Douglas fir canopies because of low light transmission, and grew best under mountain beech canopies. Lodgepole pine showed the strongest growth response to stand type while Douglas fir showed the weakest response, the weaker response being attributed to the greater shade tolerance of Douglas fir. Seedlings of both conifers in our study persisted under the moderate- and dense-canopy positions 3 years after sowing, but many appeared weak and unlikely to survive. Shade tolerance has been found to decline with increase in seedling size, especially in less shade tolerant species (Lusk 2004; Kneeshaw et al. 2006; Lusk et al. 2008) so the vigour of seedlings in under-canopy positions may further decline as seedlings age. In contrast, seedlings in the open positions generally appeared robust and likely to survive, although there was substantial variation in colour (from pale yellow to deep green) and development of height growth, suggesting variation in mycorrhizal development. Thus, the relationships between seedling number and LAI will almost certainly change with time. Further assessments will confirm survival patterns of the two species in relation to LAI. Establishment of both conifers was substantially greater under mānuka than kānuka stands. Poor establishment at the Eyrewell site was almost certainly caused by low moisture availability as it is located on a shallow free-draining Lismore soil with low water storage capacity. There is no obvious climatic explanation for the poor establishment at Ellangowan and Okuti sites. Rainfall was favourable at both sites (data not presented), while summer temperatures are similar and winter temperatures more benign than at any of the mānuka sites. Browsing of seed by invertebrates or mice (*Mus musculus*) may have contributed to the low seedling numbers at both sites as, although the plots were caged, the wire mesh covering would not have precluded their entry. Pine seeds are subject to intense predation by vertebrates, including rodents, in North America (Vander Wall 1994). In New Zealand, seeds of *Nothofagus solandri* var. *cliffortioides* trees may be heavily predated by mice (Ruscoe et al. 2005). Vander Wall (1994) found that *Pinus jeffreyi* seeds placed under litter were removed by vertebrates much more slowly than seeds placed on the surface of bare mineral soil or buried in bare mineral soil with the wing exposed. In the present study the Okuti and Ellangowan sites differed from the remaining sites in that they had high amounts of bare soil in the dense-canopy and, at Okuti, moderate-canopy and edge positions. It is possible that seed removal by mice may have been enhanced by the greater amount of bare soil, contributing to low seedling numbers at these sites. Our results indicate that Douglas fir is better able to establish in shaded environments in native woody communities than Corsican pine. Although seedlings of both species persist under canopies of both kānuka and mānuka stands in the present study, it appears unlikely that either conifer will ultimately survive under dense intact canopies. However, in disturbed or regenerating communities, both Douglas fir and Corsican pine are likely to find microsites that are suitable for establishment, with Douglas fir establishing most readily along stand edges and under moderately dense canopies and Corsican pine (and other pine species) establishing more readily in open environments between stands. Because of the taller stature of shrubland, conifer seedlings and young plants are much more difficult to detect there than in grassland or other low-stature communities and, therefore, more difficult to remove. Detection will be aided by concentration of search effort in stand openings and along stand boundaries. However, the most effective means of preventing invasion of kānuka and mānuka and other woody shrubland communities by conifer

Species	Common	Shade tolerance
		species will be to remove conifer stands that have potential to disperse seed into those communities." (Davis et al.2011) "This exploratory study examined the variation in shade tolerance of Douglas fir, western hemlock, and western red cedar in coastal British Columbia. To analyze the light environment-growth performance relationship, canopy transmittance, height increment, diameter at the base of the leader, vigor, vegetation competition, and ground surface materials data were obtained for naturally established or planted seedlings from 50 study sites which were located across a wide range of climatic and soil moisture conditions. Relationships between the percent of above-canopy light (in the photosynthetically active wavelengths (400-700 nm) associated with each seedling and its relative height increment and leader diameter were examined for individual study sites and groups of sites according to tree species and soil moisture regimes. Results indicated occurrence of both inter- and intraspecific variation in shade tolerance. Western red cedar performed relatively better at lower light levels than western hemlock, and western hemlock better than Douglas fir. The trend of increasing light required to achieve a given level of relative growth performance with increasing available soil moisture was consistent across all three species. It is concluded that the method developed has good utility but more rigorous studies are needed to define light environment-growth performance relationships and to explain ecological and physiological mechanisms involved." (Carter and Klinka 1992) "Shade tolerant to more shade than most other conifers" (Timmins and Mackenzie 1995) Examination of differential species survival from the W to the N treatments suggests a ranking in terms of increasing shade tolerance as European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason et al.2004) "Mean survival and its response to %FS [full sun] varied among species (Fig. 1). Survival for Engelmann spruce and Douglas-fir was not significantly related to %FS whereas for ponderosa pine, it significantly decreased with decreasing %FS. At the end of the first growing season, both Engelmann spruce and Douglas-fir had almost 100% survival at all light conditions (Fig. 1A) whereas survival for ponderosa pine significantly declined with decreasing %FS (X^2 = 35.7, P < 0.001) At the end of the second growing season (Fig. 1B), mean accumulated survival for ponderosa pine (79.3%) was significantly lower than that for Douglas-fir and Engelmann spruce (95.5 and 97.6%, respectively) (X^2 = 136.0, P < 0.001). With decreasing %FS, this survival for ponderosa pine significantly decreased (X^2 = 84.4, P < 0.001) whereas for Douglas-fir and Engelmann spruce, survival was independent of %FS (X^2 = 4.12, P = 0.90 for Douglas-fir and X^2 = 12.4, P = 0.19 for Engelmann spruce). At the end of the third growing season, mean accumulated survival significantly differed among species (X^2 = 180.1, P < 0.001). This survival was 63.9, 80.6, and 96.2% for ponderosa pine, Douglas-fir, and Engelmann spruce, respectively. It significantly decreased from intermediate to low %FS for ponderosa pine (Fig. 1C) (X^2 = 48.1, P < 0.001) whereas it did not significantly differ among different levels of %FS for both Douglas-fir and Engelmann spruce (X^2 = 7.19, P = 0.62 and X^2 = 11.3, P = 0.27, respectively)." (Chen 1997) "Incense-cedar *Calocedrus decurrens* grew larger than Douglas-fir *Pseudotsuga menziesii* in cool temperatures under all 3 light intensities used (5, 24 and 420 µE.m-2.s-1), but Douglas-fir grew as large or larger than incense-cedar in warm temperatures under light intensities of 24 and 420 µE. Relative allocation of

Species	Common	Shade tolerance
		growth to shoots and roots was allometric and similar for warm and cool temperatures under 24 and 420 µE in incense-cedar seedlings but not in Douglas-fir seedlings. Incense-cedar seedlings were more shade tolerant than Douglas-fir seedlings. High temperatures reduced the shade tolerance of both species." (Minore 1988)
Larix decidua	European larch	European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason 2004) Hybrid larch (*Larix x eurolepis*) is light-demanding (Kennedy 2007) "[European] Larch seedlings grown in complete darkness or low light intensity (0.5 µmol photons m^{-2} s^{-1} PAR) are characterized by etiolated or very pale green phenotypes (Fig. 1a). This is in contrast to Norway spruce seedlings, which are significantly greener, if cultivated under the same conditions (Fig. 1b)." (Stolárik,et al.2018) In general, the rate of net photosynthesis (AN) was higher in larch seedlings than in spruce seedlings. Only the spruce seedlings growing at 0.5 µmol photons m^{-2} s^{-1} PAR exceeded AN in the larch at low light intensities; the light compensation point was significantly lower in spruce than in the larch cotyledons (Table 1), indicating an effective utilization of the limited number of photons for CO_2 assimilation in accordance with high Fv/Fm values at 0.5 µmol photons m^{-2} s^{-1} PAR in spruce (Fig 5.)....Our study confirmed the reduced ability to synthesize chlorophyll in the dark in L. decidua (Figs. 1, 2a), as was found previously, which is caused by ineffective chlB (DPOR subunit) mRNA editing (Karpinska et al. 1997; Demko et al. 2009)....Our study clearly showed that under shade conditions (0.5–20 µmol photons m^{-2} s^{-1} PAR) larch cotyledons had a lower maximum quantum yield of PSII photochemistry (Fv/Fm) in comparison to spruce (Fig. 5). Thus, it is evident that, mainly under 0.5 µmol photons m^{-2} s^{-1} PAR, the LPOR enzyme cannot provide sufficient amounts of chlorophylls for the stabilization of chlorophyll binding proteins in thylakoid membranes and effective photochemistry in larch, where the DPOR enzyme is almost inactive." (Stolárik,et al.2018) Examination of differential species survival from the W to the N treatments suggests a ranking in terms of increasing shade tolerance as European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason et al.2004)
Larix laricina	tamarack	"Tamarack is very intolerant of shade. Although it can tolerate some shade during the first several years." (Burns and Honkala 1990) Shade: tolerant of partial shade, intolerant of dense shade in establishment (Timmins and Mackenzie 1995) "*Larix* is also regarded as less shade tolerant than *Picea glauca* (Logan1973)" (Brown et al.1988)
Larix occidentalis	western larch	"Tamarack is very intolerant of shade. Although it can tolerate some shade during the first several years." (Burns and Honkala 1990) Shade: tolerant of partial shade, intolerant of dense shade in establishment (Timmins and Mackenzie 1995) Examination of differential species survival from the W to the N treatments suggests a ranking in terms of increasing shade tolerance as European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason et al.2004) "*Larix* is also regarded as less shade tolerant than *Picea glauca* (Logan1973)" (Brown et al.1988)

Species	Common	Shade tolerance
Sequoia sempervirens	Coastal redwood	"Juvenile growth of redwood is best in full sunlight. Although redwood seedlings can endure heavy shade, growth there is slow. Photosynthetic capacity in redwood is remarkably high at low light intensities and keeps increasing as light intensity increases, much like more intolerant species. Redwood grew vigorously in much weaker light than 12 other tree species studies. For example, it increased its size 8.8 times in 10 percent of full sunlight in a g-month period, more than twice the growth of any of the other species in the test. For appreciable growth, Engelmann spruce (*Picea engelmannii*) and Douglas-fir require twice as much light as redwood. Pine requires three to four times as much" (Burns and Honkala 1990) Redwood > Engelmann spruce (*Picea engelmannii*) and Douglas fir > Pine (Burns and Honkala 1990) "It is probably most accurately classed as very tolerant of shade in most situations." (Burns and Honkala 1990) "*Sequoia sempervirens*—Sequoia seedlings given end of-day far-red light (1FR) had significantly greater hypocotyl extension (an average of 25%), epicotyl extension (an average of 41%), first internode extension (an average of 45%), and total number of needles (an average of 11%) than those seedlings receiving white light only (2FR) or far-red followed by red light (1FR/R) (Table 1). The significant difference between the 1FR and 1FR/ R treatments indicates that the response is photoreversible. Neither leaf area nor biomass were significantly influenced by the light treatments. Although light treatments did not significantly alter the chlorophyll a/b ratio, there was an average of 20% more chlorophyll and 42% more anthocyanin in the 1FR/R treatment compared to the other treatments (Table 1)." (Peer et al.1999) "Sequoia seedlings are sun adapted, exhibiting a photoreversible shade-avoidance response for extension growth of the hypocotyl, epicotyl, and first internode (Table 1). The photoreversal of the far-red light-induced extension by red light demonstrates that phytochrome is the mediator of the response and not chlorophyll. The internode extension response is not advantageous on the densely shaded forest floor of the redwood forest, because it would be difficult for the seedlings to become established. However, it would be advantageous in areas of partial shade in open areas such as forest gaps where seedlings may be in competition from successful sprouts." (Peer et al.1999)
Sequoiadendron giganteum	Giant redwood	"Giant sequoia is shade intolerant throughout its life." (Burns and Honkala 1990)
Picea abies	Norway spruce	
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	European larch = Scots pine < Sitka spruce = Douglas fir < western hemlock. (Mason 2004) "[…] in the case of western red cedar and Sitka spruce there appears to be contradictory evidence from these characteristics as to their shade tolerance ranking." (Kennedy 2007) Douglas-fir < Sitka spruce < hemlock (Burns and Honkala 1990)

Species	Common	Shade tolerance
		"The species chosen for this study were selected to represent a range of shade tolerances with hybrid larch classed as a light demanding species, Sitka spruce variably described as light-demanding, shade-tolerant or intermediate in its light requirements while western red cedar is considered to be shade-tolerant." (Kennedy et al.2007)
Abies grandis	grand fir	"On moist sites it grows rapidly enough to compete with other seral species in the dominant overstory. On dry sites it becomes a shade-tolerant understory and eventually assumes dominance as climax conditions are approached" (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Seedlings are quite shade-tolerant but do die in dense shade under old-growth forest and do not become established under young, dense, even-aged stands" (Burns and Honkala 1990) Port-Orford-cedar is tolerant of shade and of competition in natural stands." (Burns and Honkala 1990)
Thuja plicata	western red cedar	"[…] in the case of western red cedar and Sitka spruce there appears to be contradictory evidence from these characteristics as to their shade tolerance ranking." (Kennedy 2007) Tolerance: Western Red Cedar > Western Hemlock > Amabilis Fir (Weber 2017) "Only Pacific silver fir, western hemlock, and Pacific yew are more tolerant of shade than western red cedar" (Burns and Honkala 1990) "The species chosen for this study were selected to represent a range of shade tolerances with hybrid larch classed as a light demanding species, Sitka spruce variably described as light-demanding, shade-tolerant or intermediate in its light requirements while western red cedar is considered to be shade-tolerant." (Kennedy et al.2007) "In both hybrid larch and Sitka spruce the H:D ratio increased with increasing shade with the ratio in the most shaded plots being 30% higher for both species than the ratio in the unshaded plots. In contrast, the relative increases in the H:D ratio in western red cedar with increasing shade were much lower." (Kennedy et al.2007) "Initial survival of planted seedlings after the first growing season differed among the species and for the two light treatments (Fig. 1, top panel). Redcedar and hemlock both had high first-year survival rates in edge and interior plots (100.0 ± 7.5%, and 99.1 ± 2.4% for redcedar; 93.9 ± 5.4% and 98.4 ± 12.2% for hemlock, respectively); amabilis fir had high survival in edge plots (97.6 ± 9.6%) but much lower survival in the stand interior (59.1 ± 31.4%). At the time of harvest in May 2001, four growing seasons after the first assessment, survival for the whole 1997– 2001 period remained uniformly high for redcedar in both interior and edge locations. Hemlock had lower and somewhat more variable survival than redcedar in edge plots, and much lower and more variable survival in interior plots. Fir had high survival in edge plots but very low survival in interior plots (Table 2)" (Weber et al.2017)

Species	Common	Shade tolerance
Cryptomeria japonica	Sugi, Japanese cedar	"The regeneration process of Cryptomeria japonica forests was studied from surveys of age and initial growth of the coniferous stumps in plots of 2.66 ha in total on Yakushima Island, south Japan. The conifers germinated during particular regeneration periods each of which was shorter than 100 years. The periods repeated themselves several times in each plot, and conifers of each period formed patches. Both tree cutting and natural gap formation of the canopies initiated the regenerations. The saplings that were thought to have germinated before the initiation of the regeneration grew slowly. After the initiation, the saplings that germinated earlier grew more quickly. For the three codominant conifers: *Cryptomeria japonica*, *Tsuga sieboldii*, and *Abies firma*, the shade tolerance was inversely correlated with maximum age. Even the most shade-tolerant *A. firma* was a gap-dependent species in regeneration periods, and there were no species differences in the colonizing times during the regeneration period. Shade-intolerant long-lived species and shade-tolerant short-lived species coexisted as climax species, not as alternate species in the sere of succession." (Suzuki and Tsukahara 1987)
Cedrus deodara	Deodar cedar	

S13. Freezing tolerance

Species	Common	Freezing tolerance
Pinus contorta	lodgepole	"Lodgepole pine, with probably the widest range of environmental tolerance of any conifer in North America, grows in association with many plant species" (Burns and Honkala 1990) "High tolerance to temperatures as low as –196 °C" (Hawkins 2003) frost tolerant when established, intolerant when germinating (frost heave) (Timmins and Mackenzie 1995) "Survival of interior spruce, Douglas-fir and western red cedar seed was high even after dry seeds were frozen to low temperatures. After freezing to –40, –80 or –196 °C, germination of three of the seedlots of interior spruce ranged from 88 to 96% after 30 days in the growth chamber. Germination of Seedlot 30537 after freezing to –196 °C was only 32%, which was significantly less ($P < 0.01$) than the mean of 92% for the other three seedlots in the same freezing treatment. Mean germination of Douglas-fir seedlots ranged from 84 to 95% after all of the low temperature treatments. Three western red cedar seedlots in the –196 °C treatment had 89–94% germination, whereas mean germination of Seedlot 41265 was only 68% after freezing to –196 °C. Germination of lodgepole pine seeds was inhibited by freezing to –196 °C (53–82% germination versus 92–96% germination for the same seedlots after freezing to –40 or –80 °C). The low temperature treatments did not affect the speed of germination of lodgepole pine, Douglas-fir or western red cedar seeds, whereas interior spruce seeds frozen to –196 °C germinated more slowly than seeds frozen to –40 or –80 °C. At Day 5, germination of interior spruce seeds averaged 45 ± 2.5%, 44 ± 2.1% and 33 ± 2.6% in the –40, –80 and –196 °C treatments, respectively" (Hawkins et al.2003) "Effect of seed treatment: Survival after a freezing treatment was significantly affected by seed treatment for all species ($P < 0.001$). In most ANOVAs, there were significant interactions ($P < 0.05$) between seedlot and seed treatment (Figures 1–4); however, in all cases except one, the percentage of variation accounted for by seed treatment was more than twice that of the interaction (Table 2). Imbibed, stratified and 2-day seeds of interior spruce, lodgepole pine and Douglas-fir had the highest survival after freezing (Figures 1–3). Dry, 2- and 5-day western red cedar seeds had the highest post-freezing survival (Figure 4). After 5 days in the growth chamber, interior spruce seed in the –9 and –15 °C freezing treatments exhibited a significant decrease in survival relative to imbibed, stratified and 2-day seeds. Survival of 15- 20- and 30-day germinants of most seedlots frozen to –4 and –9 °C increased significantly ($P < 0.05$) compared with 10-day germinants (Figures 1a and 1b). Two-day lodgepole pine seeds were significantly ($P < 0.05$) less hardy than stratified and imbibed seeds when frozen to –15 °C, and 5- and 10-day germinants had poorer survival than 2-day seeds when frozen to –9 and –15 °C (Figures 2b and 2c). Survival of 15-, 20- and 30-day germinants was highly variable among seedlots of lodgepole pine after exposure to –4 or –9 °C treatment (Figures 2a and 2b), as indicated by the relatively large variance component for the seedlot × seed treatment interaction (Table 2). Survival of Douglas-fir after a freezing treatment was lowest in 10-day germinants, but was significantly greater ($P < 0.05$) in 20- and 30-day germinants of most seedlots frozen to –6 °C (Figure 3a). Western red cedar germinants had poor survival after freezing to –10 and –14 °C once they had been exposed to growing conditions for 15 days (Figure 4). After freezing to –6 °C, there was greater survival in 20-day germinants than in 15-day germinants, but survival was low for 30-day germinants (Figure 4a)." (Hawkins et al.2003)

Species	Common	Freezing tolerance
		"Seed and germinant survival was significantly greater for lodgepole pine than for interior spruce ($P < 0.04$) after freezing to –9 and –15 °C. Lodgepole pine averaged 62 ± 3.5% survival at –9 °C, and 32 ± 3.5% survival at –15 °C, whereas the corresponding values for interior spruce were 55 ± 3.5% and 29 ± 3.2% survival. Plotting the LT50 for each seed treatment revealed that interior spruce seeds were generally less hardy than seeds of the other species during the first 10 days of germination (Figure 5). However, the pattern of loss of hardiness with the progression of germination was similar for interior spruce, lodgepole pine and Douglas-fir, whereas the trend was delayed in western red cedar (Figure 5). After 30 days in the growth chamber, western red cedar and Douglas-fir were slightly less hardy, on average, than interior spruce and lodgepole pine (Figure 5)." (Hawkins et al.2003) "Germination and the correlation with cold hardiness: Speed of germination differed significantly ($P < 0.01$) among seedlots of interior spruce, Douglas-fir and western red cedar (Figure 6, Table 4). On Day 5, interior spruce averaged 45% germination, whereas Douglas-fir averaged 26% germination. Western red cedar seedlots had very few germinants until after Day 5 (Table 4), and Seedlot 41265 was the slowest to germinate. All seedlots of lodgepole pine germinated quickly, with 89% of seed germinating within 5 days in the growth chamber. By Day 10, > 50% of lodgepole pine germinants were in the cotyledon stage, whereas this stage was not reached until Day 15 in interior spruce and Day 20 in Douglas-fir and western red cedar (Table 4). For seedlots of interior spruce and lodgepole pine, speed of germination and freezing tolerance after 10 days in the growth chamber were uncorrelated. Douglas-fir and western red cedar seedlots that germinated quickly were least hardy, and seedlots that germinated later were most hardy after 10 (Douglas-fir) or 15 (western red cedar) days in the growth chamber. The interaction of seedlot and seed treatment was significant ($P < 0.001$) in the analysis of water content of interior spruce and western red cedar germinants; however, the general trends were similar for all seedlots within a species. Interior spruce, lodgepole pine and Douglas-fir showed a general decline in seedling water content with increased time in the growth chamber (Figure 7). Water content of western red cedar germinants was greatest on Day 15, and did not differ significantly among other day" (Hawkins et al.2003) "We found a pattern of decreased freezing tolerance from dry to imbibed to stratified seed, with further decreases during seed germination, followed by a slight recovery in freezing tolerance with seedling age. Dry seeds of all study species showed high tolerance to temperatures as low as –196 °C, although lodgepole pine seed and germinants experienced some damage at this temperature. Imbibed seeds were often less freezing tolerant than dry seeds. Survival of imbibed seeds frozen to –25 °C (data not shown) ranged from 15 to 55% for seedlots of interior spruce, 25 to 58% for lodgepole pine, 0 to 11% for Douglas-fir and 71 to 86% for western red cedar. In interior spruce and lodgepole pine, the next greatest decrease in freezing tolerance occurred between 0 and 5 days in the growth chamber when the radicle was just beginning to emerge. In Douglas-fir, freezing tolerance was lost at a relatively uniform rate between 0 and 10 days under warm conditions, corresponding to the slower germination in this species. Western red cedar seeds did not begin to lose freezing tolerance until they had been in the growth chamber for more than 5 days. Unlike the other species, western red cedar seed was not imbibed; therefore the delay in germination and loss of freezing tolerance was likely associated with delayed imbibition. After 5 days in the growth chamber, most western red

Species	Common	Freezing tolerance
		cedar seedlots lost freezing tolerance at a relatively uniform rate, reaching a minimum after 15 days. Western red cedar radicles emerged on Day 7 or 8. This pattern supports the generalization that treatments resulting in the loss of dormancy (e.g., stratification) do not immediately result in loss of cold hardiness. It is only after germination begins that freezing tolerance declines in proportion to elongation of the radicle (Sakai and Larcher 1987)." (Hawkins et al.2003) "Maximum cold hardiness prior to the March dehardening was below -60 °C, while the minimum cold hardiness at the end of artificial dehardening was -7 °C to -10 °C. Differences in cold hardiness among the 4 species were significant at the early stage of December dehardening (CGDH < 4000), with black spruce and white spruce 10 °C hardier than jack pine and 20 °C hardier than lodgepole pine." (Man et al.2017) "In early spring (late March, Fig. 1), visible needle death was evident for all species after they were exposed to -25 °C and -35 °C for 30 minutes ($P < 0.001$ for temperature effect) (Fig.6a). At the time of the freezing test, seedling cold hardiness determined by ambient thermal accumulation (CGDH above 0 °C since January 1was about 1500) on March dehardening curves was -25 °C for lodgepole pine, -28 °C for jack pine, and -31 °C for black and white spruce (Figs. 3 and 5). Lodgepole pine was the only species with a substantial increase in needle death, from 5% to over 40%, with a decrease in testing temperature from -25 °C to -35 °C, although the effects of tree species ($P = 0.368$) and species by temperature interaction ($P = 0.083$) were not statistically significant. In the late spring freezing test (early May, Fig. 1), needle death exceeded 50% at -10 °C and -15 °C for all 4 species ($P < 0.001$ for temperature effect) (Fig. 6b) when the cold hardiness determined by ambient thermal accumulation (CGDH was about 5800) on March dehardening curves was -9.8 °C for lodgepole pine, -11.5 °C for jack pine, -10.7 °C for white spruce, and -13.4 °C for black spruce, respectively. The point at which needle death occurred differed among the 4 conifer species ($P = 0.028$), with the highest differences between white spruce and jack pine" (Man et al.2017) "The March freezing caused>20% needle mortality on black spruce and white spruce at −25 and −35 °C and >40% needle and >25% seedling mortality on lodgepole pine at −35 °C (Figs. 1 and 2), and delayed time to budbreak for all species except jack pine at −35 °C (Fig. 3). First year shoot growth decreased as freezing temperature decreased for black spruce and white spruce for both terminals and top laterals, and for lodgepole pine for terminals (Figs. 4 and 5). The March freezing, however, did not affect second year shoot growth (Figs. 4 and 5) and reduced number of top laterals only for black spruce (Fig. 6). The May freezing caused >40% needle mortality on all 4 species at −10 and −15 °C and terminal bud mortality on white spruce at −15 °C (Figs. 1 and 7). First year terminal and top lateral growth decreased with decreasing freezing temperatures on all 4 species, except for jack pine, whereas second year growth was reduced only on black spruce and jack pine (Figs. 4 and 5). The May freezing did not afect time to budbreak for black spruce and white spruce (Fig. 3) or the number of top laterals in any of the 4 species (Fig. 6). After both the March and May freezing, dead pine needles remained attached longer than spruce needles and were more noticeable because of their size and colour change." (Man et al.2021)
Pinus sylvestris	Scots	"An unexpected result was that P. nigra had a slightly higher frost tolerance than *P. sylvestris*". (Fernandez 2018)

Species	Common	Freezing tolerance
		"Needle samples of six provenances each of lodgepole pine and Scots pine, originating from latitudes 55-68°N in W Canada and N Sweden, were collected during the autumn and subjected to freezing temperatures in the range of -8 to -29°C on three occasions in September and October. Chlorophyll a fluorescence data showed a highly significant correlation with visual assessments of injury, indicating that the technique can be used as a simple, non-destructive and objective measure for rapid detection of freezing injury and for ranking of needle materials with respect to development of cold acclimation. During autumn, lodgepole pine needles were more hardy and acclimated to low temperatures earlier than Scots pine needles." (Lindgren and Hallgren 1993) "ΔR Pmax -18±5 °C (Christersson, 1978; Leinonen et al., 1995a)" (Leinonnen 1996) "In August, the frost hardiness of stems (between –4.9°C and –6.5°C) did not differ significantly between provenances; however, from the beginning of September until early October the relationship was obvious (Table 2). Frost hardening was initiated in September, first in the northern provenances, then in the intermediate provenances and finally in the southern provenances. From the beginning of September to early October in the two northernmost provenances frost hardiness increased sharply: from –11.0°C to –35.0°C in provenance 5 and from –10.6°C to –46.1°C in provenance 6 (Table 2). During that period, the rate of hardening was 4.0°C week^{-1} and 8.5°C week^{-1} for these two northern provenances, respectively, whereas the rate of hardening for the southernmost provenance (provenance 1) was 2.8°C week^{-1}. The greatest difference in frost hardiness (27°C) between the northernmost and the southernmost provenances was found in early October. Hardening stopped for a while in October, and in four provenances it even reversed. The maximum frost hardiness ranged from ca. –38°C (southern origin) to –55°C (northern origin) without significant differences between origins at the end of November. Frost hardiness of needles: The frost hardiness of needles assessed by the electrolyte leakage method showed no differences between provenances 1–5 in August, but needles from the northernmost provenance (6) were more hardy than those from the other provenances (Table 2). Frost hardening was initiated in the beginning of September. The needles of northern provenances hardened faster than those of the southern provenances. The most significant differences between provenances were found from late September to the beginning of October, and during that time the largest difference between origins was 27°C. From mid-October until the end of the experiment, the frost hardiness of all provenances, especially the southern ones, increased significantly, indicating that the southern provenances achieved their fastest rate of hardening later than the northern ones did. At the end of November, all the provenances gained about the same level of hardiness, ranging from –80°C to –90°C. In the assessment on 30 November, the electrolyte leakage method failed to give reliable estimates of frost hardiness. According to visual scoring of damage, in August the needles in the northernmost provenance (6) were hardier than those in the southernmost provenances (Table 2). From late September until early October the frost hardiness of all provenances increased with high rates. The northern provenances hardened faster than the southern ones did, e.g. 12°C week^{-1} and 5°C week^{-1} for the northernmost and the southernmost provenance, respectively. The largest difference in frost hardiness was 34°C, which occurred between provenances 5 and 1 on 19 October. Temporarily there was a slowing of hardening, even dehardening, on 19 October, but the phenomenon was not as clear as in stems. At the end of November, the frost hardiness of

Species	Common	Freezing tolerance
		needles of all provenances was higher than–100°C; most of the needles treated at a temperature of –130°C survived. " (Repo et al.2000) "Frost hardiness between origins: In both stems and needles, the frost hardiness of different provenances in August was between –5°C and –8°C. At the end of the growing season, the frost hardiness of stems and needles varied between –5°C and –8.5°C for first-year seedlings (Hurme et al. 1997) and from –4°C to –5°C for second-year seedlings (Rikala and Repo 1987; Repo et al. 1994; Ryyppö et al. 1997). Usually the origin has not been found to affect frost hardiness during the growing season (Aho and Pulkkinen 1991; Toivonen et al. 1991), as was also shown in the present study for the stems but not in needles (3 and 24 August, Table 1)" (Repo et al.2000) "In all species, fitted curves of survival against freezing temperatures were highly significant ($P < 0.001$). Frost survival significantly differed among species (Figure 1) with a two-fold LT50 variation between *P. halepensis*, the species with the lowest LT50, and P. nigra, the species with the highest LT50. *Pinus nigra*, *P. sylvestris* and *P. uncinata* did not show any mortality until −15 °C, while at this temperature survival of *P. halepensis* and P. pinea was only around 20%. Four groups according to their LT50 values and confidence intervals were distinguished: *P. halepensis* = *P. pinea* > *P. pinaster* > *P. sylvestris* = *P. uncinata* > *P. nigra*. The survival curve was similar for *P. sylvestris* and *P. uncinata*, and their LT50 values were slightly higher than those estimated for *P. nigra*. *Pinus pinaster* had lower frost survival than *P. uncinata*, *P. sylvestris* and *P. nigra*, but higher frost survival than the Mediterranean pines *P. halepensis* and *P. pinea*, which showed little frost survival differences between them." (Fernández-Pérez et al.2018)
Pinus mugo complex	mountain	This accounted for virtually all seedlings surviving until the first winter and is a problem which on exposed. surfaces would be difficult to counter. Observations during periods of frost have indicated that the degree of damage is influenced- not so much by the severity of any one frost as by the type of frost which occurred. Graber (1971) states that moisture availability and the nature of the temperature fluctuations around. 0°C are the factors most influencing the form of frost heave. On open subsoil areas the amount of surface moisture determines whether the soil surface rises in needle form or as a solid unbroken sheet. When the ground is saturated, and the surface rises as one solid sheet very few seedlings can avoid being lifted. When the ground is moist but not saturated, needle ice develops and if no thaw occurs during the day continuing night frosts can increase the height of needle ice to dramatic levels. In the Craigieburn Range ice needle development to a height ofl 10-12 cm is not uncommon. If seedlings survive the first 2-3 cm of lift subsequent needle elongation is unlikely to damage them but needles arise and are thawed frequently over winter and during each lift seedlings are at risk." (Ledgard 1978) "In all species, fitted curves of survival against freezing temperatures were highly significant ($P < 0.001$). Frost survival significantly differed among species (Figure 1) with a two-fold LT50 variation between *P. halepensis*, the species with the lowest LT50, and *P. nigra*, the species with the highest LT50. *Pinus nigra*, *P. sylvestris* and *P. uncinata* did not show any mortality until −15 °C, while at this temperature survival of P. halepensis and *P. pinea* was only around 20%. Four groups according to their LT50 values and confidence intervals were distinguished: *P. halepensis* = *P. pinea* > *P. pinaster* > *P. sylvestris* = *P. uncinata* > *P. nigra*. The survival curve was similar for *P. sylvestris* and *P. uncinata*, and their LT50 values were slightly higher than those estimated

Species	Common	Freezing tolerance
		for *P. nigra*. *Pinus pinaster* had lower frost survival than *P. uncinata*, *P. sylvestris* and *P. nigra*, but higher frost survival than the Mediterranean pines *P. halepensis* and *P. pinea*, which showed little frost survival differences between them." (Fernández-Pérez et al.2018)
Pinus nigra	black, Austrian	"An unexpected result was that *P. nigra* had a slightly higher frost tolerance than P. sylvestris". (Fernandez 2018) " "High N increased frost tolerance in *P. nigra*, the psychrophilic species that lives in cold winter locations and has strong endodormant control of growth and cold acclimation" (Toca 2018) "The northern varieties are very frost-hardy, withstanding temperatures of -30°C (-22°F), and the southern varieties tolerate -7°C (19°F) temperatures." (Burns and Honkala 1990) frost: slightly tolerant (Timmins and Mackenzie 1995) "In all species, fitted curves of survival against freezing temperatures were highly significant ($P < 0.001$). Frost survival significantly differed among species (Figure 1) with a two-fold LT50 variation between *P. halepensis*, the species with the lowest LT50, and *P. nigra*, the species with the highest LT50. *Pinus nigra*, *P. sylvestris* and *P. uncinata* did not show any mortality until −15 °C, while at this temperature survival of P. halepensis and *P. pinea* was only around 20%. Four groups according to their LT50 values and confidence intervals were distinguished: *P. halepensis* = *P. pinea* > *P. pinaster* > *P. sylvestris* = *P. uncinata* > *P. nigra*. The survival curve was similar for *P. sylvestris* and *P. uncinata*, and their LT50 values were slightly higher than those estimated for *P. nigra*. *Pinus pinaster* had lower frost survival than *P. uncinata*, *P. sylvestris* and *P. nigra*, but higher frost survival than the Mediterranean pines *P. halepensis* and *P. pinea*, which showed little frost survival differences between them." (Fernández-Pérez et al.2018) "Species differed in VDI after root freezing at −10 °C both in November and January (Table 1). *Pinus halepensis* and *P. pinea* had the highest VDI values, with no significant differences between them (30.6% ± 6.7 in November and 36.2% ± 9.3 in January for *P. halepensis* and 26.0% ± 5.7 and 33.5% ± 9.4, respectively for P. pinea). In contrast, P. nigra had the lowest VDI values (7.6% ± 1.5 and 2.6% ± 0.6 in November and January, respectively), while *P. pinaster* had intermediate VDI values (12.4% ± 1.5 and 20.9% ± 3.4 in November and January, respectively) between *P. nigra* and the other pine species (Figure 1)...In January, after a −15 °C frost VDI significantly differed among species (Table 1), with *P. halepensis* and *P. pinea* showing the highest values (59.3% ± 8.8 and 41.3% ± 5.2, respectively) followed by P. pinaster (17.8% ± 2.0) and *finally P. nigra*, which had the lowest VDI value (3.4% ± 0.5). We found a marginally significant Species × Fertilization interaction ($P = 0.065$), explained by a maximum VDI of high fertilized *P. halepensis* and *P. pinea* seedlings, that did not occur in *P. nigra* and in *P. pinaster* (Figure 2b). On average, shoot VDI after −15 °C frost decreased strongly from November to January (69.4% ± 4.3 and 29.7% ± 3.6, respectively). In January, all seedlings of *P. halepensis*, *P. pinea* and *P. pinaster* died after the −23 °C frost test. In contrast, most *P. nigra* seedlings survived with fall fertilized and pre-hardening high fertilized seedlings having the lowest VDI values, without significant differences between them (9.3% ± 2.4 and 16.8% ± 5.5, respectively), while low fertilization had the highest (32.5% ± 7.7) (Species × Fertilization interaction, Table 1)" (Toca et al.2018) (VDI = visual damage index)

Species	Common	Freezing tolerance
Pinus ponderosa	Ponderosa	"Many variables cause seedling mortality. Ponderosa pine seedlings less than 36 days old were more susceptible to minimum night temperatures (lower than -5° C (23° F)) than were lodgepole pine seedlings. But by 2 months of age, differences in tolerance did not exist." (Burns and Honkala 1990) "During winters with little snow cover, 1- and 2-year-old seedlings suffered damage and killing from frost." (Burns and Honkala 1990) "In the Southwest, natural regeneration on fine-textured soils is almost non-existent because of frost-heaving." (Burns and Honkala 1990)
Pinus muricata	bishop	
Pinus pinaster	maritime	"Frost tolerance was significantly higher in P. pinaster than in two species with which it frequently coexists, *P. halepensis* and *P. pinea*" (Fernandez 2018) "N fertilization had little effect on the frost tolerance of the mesophilic species *P. pinaster*." (Toca 2018) frost: intolerant (Timmins and Mackenzie 1995) "In all species, fitted curves of survival against freezing temperatures were highly significant ($P < 0.001$). Frost survival significantly differed among species (Figure 1) with a two-fold LT50 variation between *P. halepensis*, the species with the lowest LT50, and *P. nigra*, the species with the highest LT50. *Pinus nigra*, *P. sylvestris* and *P. uncinata* did not show any mortality until −15 °C, while at this temperature survival of P. halepensis and *P. pinea* was only around 20%. Four groups according to their LT50 values and confidence intervals were distinguished: *P. halepensis* = *P. pinea* > *P. pinaster* > *P. sylvestris* = *P. uncinata* > *P. nigra*. The survival curve was similar for *P. sylvestris* and *P. uncinata*, and their LT50 values were slightly higher than those estimated for *P. nigra*. *Pinus pinaster* had lower frost survival than *P. uncinata*, *P. sylvestris* and *P. nigra*, but higher frost survival than the Mediterranean pines *P. halepensis* and *P. pinea*, which showed little frost survival differences between them." (Fernández-Pérez et al.2018)
Pinus radiata	Monterey	"Frost intolerant " (Timmins and Mackenzie 1995) "In summer, radiata pine will tolerate without damage minimum temperatures of about -6°C and gradually during the late summer, autumn, and winter it will harden off to tolerate temperatures of about -12°C by August" (Rook and Whitehead 1979) "Frost and drought can cause high mortality in the first year or two after planting" (Burdon 1992) Frost was not a problem at both sites...Survival exceeded 90%; frost did not exceed -3.5°C in summer and -8.3°C in winter. (Menzies and Chavasse 1982)

Species	Common	Freezing tolerance
		"As a group, the non-Florida *P. taeda* sources were more frost tolerant than the three P. radiata sources. There was some indication that *P. radiata* var. *binata* and *P. radiata* from Chile might be slightly more frost tolerant than the P. radiata from California, but these differences were not statistically significant (p = 0.26 and 0.16, respectively)." (Hodge et al.2012) "*Pinus radiata* is also moderately cold hardy, but less so than P. greggii var. australis. Temperatures in natural populations of *P. radiata* in California rarely fall to −6 to −7 °C (Dvorak 1991), but there is little information available about the cold tolerance of island populations (Rogers 2002)" (Hodge et al.2012)
Pinus x attenuata	knobcone	Higher cold tolerance [compared to radiata] (Gibson II 2022)
Pseudotsuga menziesii	Douglas fir	high tolerance to temperatures as low as –196 °C (Hawkins 2003) "Frost: intolerant in early years, tolerant when higher than 2 m tall" (Timmins and Mackenzie 1995) "Susceptibility to frost depends on the time of year. Douglas-fir is very frost-resistant in the dormant, winter phase (March to August) but can be quite susceptible when shoots are flushing in late spring. The timing of flushing depends on both the seed source and the location. To avoid risk of such damage, flat land or frost hollows are normally left unplanted or planted in other species, with Douglas-fir being restricted to sites with some degree of air drainage. At altitudes greater than 700 m, slopes of 1 or less are almost certain to kill young plants whereas remarkably slight slopes (+3) can provide sufficient downward airflow. Very young trees can easily be killed by frost, because of the loss of their entire foliage and because the temperature is often lower close to the ground, but it is rare for widespread mortality to occur with larger trees." (Maclaren et al.2009) "Survival of interior spruce, Douglas-fir and western red cedar seed was high even after dry seeds were frozen to low temperatures. After freezing to –40, –80 or –196 °C, germination of three of the seedlots of interior spruce ranged from 88 to 96% after 30 days in the growth chamber. Germination of Seedlot 30537 after freezing to –196 °C was only 32%, which was significantly less ($P < 0.01$) than the mean of 92% for the other three seedlots in the same freezing treatment. Mean germination of Douglas-fir seedlots ranged from 84 to 95% after all of the low temperature treatments. Three western red cedar seedlots in the –196 °C treatment had 89–94% germination, whereas mean germination of Seedlot 41265 was only 68% after freezing to –196 °C. Germination of lodgepole pine seeds was inhibited by freezing to –196 °C (53–82% germination versus 92–96% germination for the same seedlots after freezing to –40 or –80 °C). The low temperature treatments did not affect the speed of germination of lodgepole pine, Douglas-fir or western red cedar seeds, whereas interior spruce seeds frozen to –196 °C germinated more slowly than seeds frozen to –40 or –80 °C. At Day 5, germination of interior spruce seeds averaged 45 ± 2.5%, 44 ± 2.1% and 33 ± 2.6% in the –40, –80 and –196 °C treatments, respectively" (Hawkins et al.2003) "Effect of seed treatment: Survival after a freezing treatment was significantly affected by seed treatment for all species ($P < 0.001$). In most ANOVAs, there were significant interactions ($P < 0.05$) between seedlot and seed

Species	Common	Freezing tolerance
		treatment (Figures 1–4); however, in all cases except one, the percentage of variation accounted for by seed treatment was more than twice that of the interaction (Table 2). Imbibed, stratified and 2-day seeds of interior spruce, lodgepole pine and Douglas-fir had the highest survival after freezing (Figures 1–3). Dry, 2- and 5-day western red cedar seeds had the highest post-freezing survival (Figure 4). After 5 days in the growth chamber, interior spruce seed in the –9 and –15 °C freezing treatments exhibited a significant decrease in survival relative to imbibed, stratified and 2-day seeds. Survival of 15- 20- and 30-day germinants of most seedlots frozen to –4 and –9 °C increased significantly ($P < 0.05$) compared with 10-day germinants (Figures 1a and 1b). Two-day lodgepole pine seeds were significantly ($P < 0.05$) less hardy than stratified and imbibed seeds when frozen to –15 °C, and 5- and 10-day germinants had poorer survival than 2-day seeds when frozen to –9 and –15 °C (Figures 2b and 2c). Survival of 15-, 20- and 30-day germinants was highly variable among seedlots of lodgepole pine after exposure to –4 or –9 °C treatment (Figures 2a and 2b), as indicated by the relatively large variance component for the seedlot × seed treatment interaction (Table 2). Survival of Douglas-fir after a freezing treatment was lowest in 10-day germinants, but was significantly greater ($P < 0.05$) in 20- and 30-day germinants of most seedlots frozen to –6 °C (Figure 3a). Western red cedar germinants had poor survival after freezing to –10 and –14 °C once they had been exposed to growing conditions for 15 days (Figure 4). After freezing to –6 °C, there was greater survival in 20-day germinants than in 15-day germinants, but survival was low for 30-day germinants (Figure 4a)." (Hawkins et al.2003) "Seed and germinant survival was significantly greater for lodgepole pine than for interior spruce ($P < 0.04$) after freezing to –9 and –15 °C. Lodgepole pine averaged 62 ± 3.5% survival at –9 °C, and 32 ± 3.5% survival at –15 °C, whereas the corresponding values for interior spruce were 55 ± 3.5% and 29 ± 3.2% survival. Plotting the LT50 for each seed treatment revealed that interior spruce seeds were generally less hardy than seeds of the other species during the first 10 days of germination (Figure 5). However, the pattern of loss of hardiness with the progression of germination was similar for interior spruce, lodgepole pine and Douglas-fir, whereas the trend was delayed in western red cedar (Figure 5). After 30 days in the growth chamber, western red cedar and Douglas-fir were slightly less hardy, on average, than interior spruce and lodgepole pine (Figure 5)." (Hawkins et al.2003) "Germination and the correlation with cold hardiness: Speed of germination differed significantly ($P < 0.01$) among seedlots of interior spruce, Douglas-fir and western red cedar (Figure 6, Table 4). On Day 5, interior spruce averaged 45% germination, whereas Douglas-fir averaged 26% germination. Western red cedar seedlots had very few germinants until after Day 5 (Table 4), and Seedlot 41265 was the slowest to germinate. All seedlots of lodgepole pine germinated quickly, with 89% of seed germinating within 5 days in the growth chamber. By Day 10, > 50% of lodgepole pine germinants were in the cotyledon stage, whereas this stage was not reached until Day 15 in interior spruce and Day 20 in Douglas-fir and western red cedar (Table 4). For seedlots of interior spruce and lodgepole pine, speed of germination and freezing tolerance after 10 days in the growth chamber were uncorrelated. Douglas-fir and western red cedar seedlots that germinated quickly were least hardy, and seedlots that germinated later were most hardy after 10 (Douglas-fir) or 15 (western red cedar) days in the growth chamber. The interaction of seedlot and seed treatment was significant ($P < 0.001$) in the analysis of water content of interior spruce and western red cedar germinants; however, the general trends were similar for all seedlots within a species. Interior spruce, lodgepole pine and Douglas-fir showed a

Species	Common	Freezing tolerance
		general decline in seedling water content with increased time in the growth chamber (Figure 7). Water content of western red cedar germinants was greatest on Day 15, and did not differ significantly among other day" (Hawkins et al.2003) "We found a pattern of decreased freezing tolerance from dry to imbibed to stratified seed, with further decreases during seed germination, followed by a slight recovery in freezing tolerance with seedling age. Dry seeds of all study species showed high tolerance to temperatures as low as –196 °C, although lodgepole pine seed and germinants experienced some damage at this temperature. Imbibed seeds were often less freezing tolerant than dry seeds. Survival of imbibed seeds frozen to –25 °C (data not shown) ranged from 15 to 55% for seedlots of interior spruce, 25 to 58% for lodgepole pine, 0 to 11% for Douglas-fir and 71 to 86% for western red cedar. In interior spruce and lodgepole pine, the next greatest decrease in freezing tolerance occurred between 0 and 5 days in the growth chamber when the radicle was just beginning to emerge. In Douglas-fir, freezing tolerance was lost at a relatively uniform rate between 0 and 10 days under warm conditions, corresponding to the slower germination in this species. Western red cedar seeds did not begin to lose freezing tolerance until they had been in the growth chamber for more than 5 days. Unlike the other species, western red cedar seed was not imbibed; therefore the delay in germination and loss of freezing tolerance was likely associated with delayed imbibition. After 5 days in the growth chamber, most western red cedar seedlots lost freezing tolerance at a relatively uniform rate, reaching a minimum after 15 days. Western red cedar radicles emerged on Day 7 or 8. This pattern supports the generalization that treatments resulting in the loss of dormancy (e.g., stratification) do not immediately result in loss of cold hardiness. It is only after germination begins that freezing tolerance declines in proportion to elongation of the radicle (Sakai and Larcher 1987)." (Hawkins et al.2003) "There was a significant difference in shoot-freezing tolerance between Norway spruce and Douglas fir in the first freezing in early October (7 October 2013), see Table 3, whereas this was not found between provenances of Douglas fir. All Douglas fir provenances showed very high shoot electrolytic leakage caused by freezing to −20°C. Data from the next freezing occasion (28 October 2013) showed the difference in freezing tolerance between Norway spruce and Douglas fir provenances to be less. Caycuse River, Ladysmith, Bowser Heaman and Larch Hills were significantly separated from Norway spruce but none of the Douglas fir provenances could be separated from each other" (Malmqvist, et al.2017a) "The freezing test of buds to -5 °C in early spring showed that the buds of Norway spruce and Douglas fir were already sensitive to freezing when they were slightly swollen (stage 1, see Fig. 3). The buds of the Norway spruce and Douglas fir provenances (Ladysmith, coastal, and Three Valley, interior) were severely damaged after freezing to -5 °C, as electrolytic leakage from freezing exceeded 50% on average for all tested treatments. The average electrolyte leakage of unfrozen control samples of Norway spruce was 41% and for Douglas fir 28%. No significant differences regarding electrolyte leakage after freezing were found between species ($p = 0.258$) or between the two provenances of Douglas fir ($p = 0.650$). However, for buds that had reached stage 2 of bud development (stage 2, see Fig. 3), the electrolytic leakage was significantly higher than for buds that had reached stage 1, regardless of species or provenance ($p = 0.035$)." (Malmqvist et al.2017b)

Species	Common	Freezing tolerance
Larix decidua	European larch	Frost: intolerant at time of spring flush (Timmins and Mackenzie 1995)
Larix laricina	tamarack	
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	
Sequoiadendron giganteum	Giant redwood	
Picea abies	Norway spruce	"Bud hardiness increased over the experimental period. On August 21, buds from all groups of trees were damaged by freezing to –10 °C, whereas on October 30, there was minimal damage even after freezing to – 45 °C" (Hannerz and Westin 2005) "Frost hardiness was tested on needles from 6-years-old Norway spruces that had been cultivated for 2 years in artificial ecosystems at an atmospheric CO_2 concentration of 280, 420 or 560 ppm and a nitrogen fertilization corresponding to 0, 30, and 90 kg N ha^{-1} yr^{-1} (NH4N03) as well as combinations of these treatments. Samples of previous year's needles were taken after completion of frost hardening in autumn, and at three dates during the dehardening process in spring when potentially harmful late frost events naturally occur. The needles were exposed to freezing temperatures down to -35 °C. Samples were taken at 5·C intervals and frost injury was estimated by the electrolyte leakage technique. After autumnal hardening, needles were injured only below -25°C (LT50 < -30 °C), while after dehardening in spring the critical frost temperature (LT50) was around -10°C. Frost hardiness was not influenced by the different CO_2 and nitrogen treatments of the trees neither in autumn nor during the dehardening phase in spring" (Wiemken et al.1996) "As expected, frost injury was elicited at much lower temperatures in autumn than in spring (Fig. 2). In autumn (date of sampling between November 24 to December 8), frost damage of needles was induced only below -20 °C, since the LT50 was below -35 °C, which could not be determined exactly with the freezing equipment used. In contrast, at the first sampling date in spring (April 21), frost hardiness was significantly decreased and injury was induced already at temperatures between -15 and -20 °C. During the following month, until May 19, frost dehardening proceeded further, leading to needle injuries at about -10 °C for clone A and between -10 and -15 °C for clone X (Fig. 2). Thus, clone A dehardened slightly earlier than clone X. No significant difference in frost hardiness was detected in the needles grown under the different CO_2 and/or nitrogen treatments over the temperature range from 0 to -20 °C and at all the collection dates for both clones. SE values to the means in Fig. 2 are given in Table 3 to keep the figure readable. The temperatures inducing 50 % needle injury (LT50) for the three collection dates in spring were calculated and are depicted in Fig. 3. At the first date, April 21 the LT50 was between -25 and -15 °C, showing that dehardening was already advanced considering that at late

Species	Common	Freezing tolerance
		autumn the LT50 was well below -35 °C. On May 19, the last date of sampling, a LT50 between -10 and -15 °C was reached. This still quite high frost hardiness was probably kept during summer; in Picea rubens a LT50 of -rc has been found in August (Sheppard et al., 1989) and Picea abies belongs to the frost hardiest trees in the world (Sakai, 1983). The treatment with different concentrations of atmospheric CO_2 and/or nitrogen fertilization had again no recognizable effect on the time course of dehardening in spring. Since whole plant freezing tests and tests on plant organs or tissues have been found to give consistent relationships (Burr et al., 1990) our results on the needles should also be valid for the whole plants." (Wiemken et al.1996) "The goal of the present study was to investigate whether seedlings of Norway spruce (*Picea abies* [L.] Karst.) from a frost tolerant progeny (P2), were more drought tolerant than seedlings from a less frost tolerant progeny (P1). Progenies differing in freezing tolerance were identified by exposing seedlings in autumn in a large-scale trial to temperatures from -11 to -15 °C and scoring the degree of needle injury. Seedlings from P1 and P2 were grown from seeds for about 1 year under controlled conditions in a climatized growth room and were exposed to drought stress by withholding water for about 3 weeks. Drought caused reductions in biomass in both progenies but to a stronger extent in P1 than in P2. Seedlings of P2 were able to fully maintain root biomass. They also showed less water loss in different tissues. Decreases in quantum yield efficiency of photosystem II of dark-adapted plants occurred several days later in P2 than in P1. New proteins of molecular masses of 24.3 and 25.5 kDa appeared during drought stress." (Blödner et al.2005) “Drought is a major factor limiting tree growth in temperate forest ecosystems. On sunny days in winter, when the soil is frozen, conifers can be exposed simultaneously to both freezing and drought stress (Mayr et al., 2003). In order to withstand such unfavourable conditions, it would be advantageous, if freezing and drought tolerance were correlated traits in spruce. The most important result of our study was that we could show employing several parameters to characterise stress responses that P2, which was more freezing tolerant than P1, also was more drought tolerant." (Blödner et al.2005) "Freezing tolerance decreased during the fall, with a consistently high level of freezing tolerance during mid winter, followed by decreasing freezing tolerance in late winter and early spring (data not shown). This is the typical seasonal freezing tolerance pattern for both western redcedar [9, 13, 21] and yellow-cedar [5, 22] in coastal forests of the Pacific Northwest. Western redcedar and yellow-cedar both displayed a comparable fall decline in freezing tolerance. The LT50 values (i.e., freezing temperature at which 50% foliage electrolyte leakage occurred) of both western redcedar and yellow-cedar decreased as mean air temperature declined (Fig. 2). There was no difference in the LT50 response of populations for either species. In addition, both species had a similar decrease in LT50 values during the fall decline in air temperature. " (Grossnickle and Russell 2006)
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	"Changes in the natural level of frost hardiness of shoots of four provenances of *Picea sitchensis* were monitored over two growing seasons by detaching shoots from 7 to 10-year-old trees growing in a nursery in Scotland, and subjecting them to freezing temperatures under conditions which simulated night frosts. Six

Species	Common	Freezing tolerance
		seasonal phases of frost hardiness were identified (Fig. 3).During each autumn, killing temperatures (the level of hardiness) decreased from -5°C to below -20°C, beginning several weeks after shoot elongation ceased. Alaskan provenances hardened in September, apparently in response to shortening day lengths alone, whereas an Oregon provenance did not harden until November, after repeated frosts. Queen Charlotte Islands provenances were intermediate. From November to March all provenances were hardy to below -20°C, which is adequate to prevent direct freezing injury at most plantation sites. In March-April, several weeks before bud-burst, old shoots dehardened to killing temperatures of about -10°C in response to warm temperatures, and southerly provenances did so before northerly ones. During bud-burst the newly-emerging shoots were hardy to only -3°C to -5°C until they were about 3.5 cm long. All provenances burst bud at the same time and were equally frost susceptible at this time. During May-July the elongating shoots fluctuated in hardiness between -5°C and -10°C apparently in response to fluctuating ambient temperatures. In August 1980 there was a period of late summer dehardening to killing temperatures of about -3°C.Seasonal changes in hardiness are discussed in relation to changes in shoot growth and environmental factors. The main opportunities for selecting frost hardy genotypes seem to be in the rate of autumn hardening, the time of pre-bud burst dehardening, and the time of bud-burst" (Cannell and Sheppard 1982).
Abies grandis	grand fir	"The frost-free season varies, ranging from about 60 to more than 250 days, and is very irregular from year to year. Frosts may occur in any month in the interior." (Burns and Honkala 1990) "The needles are quite resistant to cold during the severest part of the winter. Grand fir leaves have been subjected to temperatures of -55” C (-67” F) without damage. Sudden extreme drops of temperature in the fall occasionally damage needles, but seldom are they fatal." (Burns and Honkala 1990)
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Laboratory experiments show that it is also more susceptible to freezing than most associated trees, although reports of winter damage in the field vary" (Burns and Honkala 1990) "In some instances, no damage occurred at -25°C (-13°F); others report severe damage at -13 °C (9 °F). Most drastic winter kill occurred in dry, windy, cold weather, desiccation apparently being of considerable consequence." (Burns and Honkala 1990)
Thuja plicata	western red cedar	high tolerance to temperatures as low as –196 °C (Hawkins 2003) "Absolute minimum temperatures experienced by western redcedar in British Columbia are -10° to -30° C "(Burns and Honkala 1990) "Western redcedar seedlings are less tolerant of high soil temperature and of frost than are the seedlings of Engelmann spruce, grand fir, and Douglas fir" (Burns and Honkala 1990) "Survival of interior spruce, Douglas-fir and western red cedar seed was high even after dry seeds were frozen to low temperatures. After freezing to –40, –80 or –196 °C, germination of three of the seedlots of interior

Species	Common	Freezing tolerance
		spruce ranged from 88 to 96% after 30 days in the growth chamber. Germination of Seedlot 30537 after freezing to –196 °C was only 32%, which was significantly less ($P < 0.01$) than the mean of 92% for the other three seedlots in the same freezing treatment. Mean germination of Douglas-fir seedlots ranged from 84 to 95% after all of the low temperature treatments. Three western red cedar seedlots in the –196 °C treatment had 89–94% germination, whereas mean germination of Seedlot 41265 was only 68% after freezing to –196 °C. Germination of lodgepole pine seeds was inhibited by freezing to –196 °C (53–82% germination versus 92–96% germination for the same seedlots after freezing to –40 or –80 °C). The low temperature treatments did not affect the speed of germination of lodgepole pine, Douglas-fir or western red cedar seeds, whereas interior spruce seeds frozen to –196 °C germinated more slowly than seeds frozen to –40 or –80 °C. At Day 5, germination of interior spruce seeds averaged 45 ± 2.5%, 44 ± 2.1% and 33 ± 2.6% in the –40, –80 and –196 °C treatments, respectively" (Hawkins et al.2003) "Effect of seed treatment: Survival after a freezing treatment was significantly affected by seed treatment for all species ($P < 0.001$). In most ANOVAs, there were significant interactions ($P < 0.05$) between seedlot and seed treatment (Figures 1–4); however, in all cases except one, the percentage of variation accounted for by seed treatment was more than twice that of the interaction (Table 2). Imbibed, stratified and 2-day seeds of interior spruce, lodgepole pine and Douglas-fir had the highest survival after freezing (Figures 1–3). Dry, 2- and 5-day western red cedar seeds had the highest post-freezing survival (Figure 4). After 5 days in the growth chamber, interior spruce seed in the –9 and –15 °C freezing treatments exhibited a significant decrease in survival relative to imbibed, stratified and 2-day seeds. Survival of 15- 20- and 30-day germinants of most seedlots frozen to –4 and –9 °C increased significantly ($P < 0.05$) compared with 10-day germinants (Figures 1a and 1b). Two-day lodgepole pine seeds were significantly ($P < 0.05$) less hardy than stratified and imbibed seeds when frozen to –15 °C, and 5- and 10-day germinants had poorer survival than 2-day seeds when frozen to –9 and –15 °C (Figures 2b and 2c). Survival of 15-, 20- and 30-day germinants was highly variable among seedlots of lodgepole pine after exposure to –4 or –9 °C treatment (Figures 2a and 2b), as indicated by the relatively large variance component for the seedlot × seed treatment interaction (Table 2). Survival of Douglas-fir after a freezing treatment was lowest in 10-day germinants, but was significantly greater ($P < 0.05$) in 20- and 30-day germinants of most seedlots frozen to –6 °C (Figure 3a). Western red cedar germinants had poor survival after freezing to –10 and –14 °C once they had been exposed to growing conditions for 15 days (Figure 4). After freezing to –6 °C, there was greater survival in 20-day germinants than in 15-day germinants, but survival was low for 30-day germinants (Figure 4a)." (Hawkins et al.2003) "Seed and germinant survival was significantly greater for lodgepole pine than for interior spruce ($P < 0.04$) after freezing to –9 and –15 °C. Lodgepole pine averaged 62 ± 3.5% survival at –9 °C, and 32 ± 3.5% survival at –15 °C, whereas the corresponding values for interior spruce were 55 ± 3.5% and 29 ± 3.2% survival. Plotting the LT50 for each seed treatment revealed that interior spruce seeds were generally less hardy than seeds of the other species during the first 10 days of germination (Figure 5). However, the pattern of loss of hardiness with the progression of germination was similar for interior spruce, lodgepole pine and Douglas-fir, whereas the trend was delayed in western red cedar (Figure 5). After 30 days in the growth chamber, western red cedar and Douglas-fir were slightly less hardy, on average, than interior spruce and lodgepole pine (Figure 5)." (Hawkins et al.2003)

Species	Common	Freezing tolerance
		"Germination and the correlation with cold hardiness: Speed of germination differed significantly ($P < 0.01$) among seedlots of interior spruce, Douglas-fir and western red cedar (Figure 6, Table 4). On Day 5, interior spruce averaged 45% germination, whereas Douglas-fir averaged 26% germination. Western red cedar seedlots had very few germinants until after Day 5 (Table 4), and Seedlot 41265 was the slowest to germinate. All seedlots of lodgepole pine germinated quickly, with 89% of seed germinating within 5 days in the growth chamber. By Day 10, > 50% of lodgepole pine germinants were in the cotyledon stage, whereas this stage was not reached until Day 15 in interior spruce and Day 20 in Douglas-fir and western red cedar (Table 4). For seedlots of interior spruce and lodgepole pine, speed of germination and freezing tolerance after 10 days in the growth chamber were uncorrelated. Douglas-fir and western red cedar seedlots that germinated quickly were least hardy, and seedlots that germinated later were most hardy after 10 (Douglas-fir) or 15 (western red cedar) days in the growth chamber. The interaction of seedlot and seed treatment was significant ($P < 0.001$) in the analysis of water content of interior spruce and western red cedar germinants; however, the general trends were similar for all seedlots within a species. Interior spruce, lodgepole pine and Douglas-fir showed a general decline in seedling water content with increased time in the growth chamber (Figure 7). Water content of western red cedar germinants was greatest on Day 15, and did not differ significantly among other day" (Hawkins et al.2003) "We found a pattern of decreased freezing tolerance from dry to imbibed to stratified seed, with further decreases during seed germination, followed by a slight recovery in freezing tolerance with seedling age. Dry seeds of all study species showed high tolerance to temperatures as low as –196 °C, although lodgepole pine seed and germinants experienced some damage at this temperature. Imbibed seeds were often less freezing tolerant than dry seeds. Survival of imbibed seeds frozen to –25 °C (data not shown) ranged from 15 to 55% for seedlots of interior spruce, 25 to 58% for lodgepole pine, 0 to 11% for Douglas-fir and 71 to 86% for western red cedar. In interior spruce and lodgepole pine, the next greatest decrease in freezing tolerance occurred between 0 and 5 days in the growth chamber when the radicle was just beginning to emerge. In Douglas-fir, freezing tolerance was lost at a relatively uniform rate between 0 and 10 days under warm conditions, corresponding to the slower germination in this species. Western red cedar seeds did not begin to lose freezing tolerance until they had been in the growth chamber for more than 5 days. Unlike the other species, western red cedar seed was not imbibed; therefore the delay in germination and loss of freezing tolerance was likely associated with delayed imbibition. After 5 days in the growth chamber, most western red cedar seedlots lost freezing tolerance at a relatively uniform rate, reaching a minimum after 15 days. Western red cedar radicles emerged on Day 7 or 8. This pattern supports the generalization that treatments resulting in the loss of dormancy (e.g., stratification) do not immediately result in loss of cold hardiness. It is only after germination begins that freezing tolerance declines in proportion to elongation of the radicle (Sakai and Larcher 1987)." (Hawkins et al.2003)
Cryptomeria japonica	Sugi, Japanese cedar	

Species	**Common**	Freezing tolerance
Cedrus deodara	Deodar cedar	

S14. Cold hardiness

Species	Common	Cold hardiness
Pinus contorta	lodgepole	"[…] a significant degree of cold hardiness was maintained". (Hawkins 2003) "Low temperature does not seem to be a significant factor in seedling mortality. Seedlings only 1 week old are able to tolerate growth chamber temperatures of -58C. Forty percent of the seedlings survived -98°C for one night and a few even survived -11°C. Frost mortality increased for 36-day old seedlings, but by the fall, they were able to withstand winter temperatures (Cochran and Bernsten, 1973). According to a literature review, it was determined that lodgepole pine was the most frost-tolerant tree in the northwestern US (Minore, 1979). Wali and Krajina (1973) reported that lodgepole pine occurred on sites with the coldest winter temperatures in sub-boreal ecosystems."(Despain 2001) "Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." Ledgard and Baker 1988 "On all sites species had germinated but on scree and exposed subsoils seedlings failed to survive. In a separate study of mountain pine on subsoil (67) major seedling losses were attributed to birds (100%) in unprotected plots) failure of radicle to penetrate the subsoil (15%) and frost heave (44%)." (Ledgard and Baker 1988)
Pinus sylvestris	Scots	" Scotch pine survives in the Verkhoyansk Mountains of eastern Siberia where winter temperatures have been recorded as low as -64°C (-33°F)." (Burns and Honkala 1990) "Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." Ledgard and Baker 1988
Pinus mugo complex	mountain	"Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." Ledgard and Baker 1988 "On all sites species had germinated but on scree and exposed subsoils seedlings failed to survive. In a separate study of mountain pine on subsoil (67) major seedling losses were attributed to birds (100%) in unprotected plots) failure of radicle to penetrate the subsoil (15%) and frost heave (44%)." (Ledgard and Baker 1988)
Pinus nigra	black, Austrian	"The species has been shown to carry on photosynthesis at -5°C (23°F), with respiration still detectable at -19°C (-2°F)" (Burns and Honkala 1990)

Species	Common	Cold hardiness
		"Seedlings…suffered severe frost damage in the nursery." (Burns and Honkala 1990) "Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." (Ledgard and Baker 1988)
Pinus ponderosa	Ponderosa	"Annual extremes are from -40° to 43°C (40° to 110°F)." (Burns and Honkala 1990) "Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." (Ledgard and Baker 1988)
Pinus muricata	bishop	
Pinus pinaster	maritime	"Primary cone growth was limited by extreme cold events. Absence of precipitation limits secondary growth and hinders final cone ripening. It turns out that seed production and seed rain may be a bottleneck for natural regeneration of P. pinaster under low stand densities, especially under extreme climatic scenarios" (Ruano et al.2015b) We can confirm our first hypothesis of a climate-mediated interannual seed production pattern. Specifically, all considered explanatory variables were exclusively related to cone growth and maturation. Rodríguez-Soalleiro et al. (2008) asserted that flowering in *P. pinaster* is affected by light, temperature, precipitation, and drought. We tested the effects of precipitation, wind velocity, and frost as potential surrogates, but none of them was found to be significant in our analysis. Similarly, we did not find any association between climatic variables and seed rain. Apparently, high temperatures may favour cone opening (Nathan et al. 1999; Tapias et al. 2001), although this may refer to serotinous species, and the local provenance of this study is weakly serotinous. (Ruano et al.2015b) "The positive effect of precipitation during the period of secondary cone growth points out that water stress is a limiting factor for seed production in *P. pinaster* in the Castilian Plateau. These findings coincide with those of Mutke et al. (2005) and Calama et al. (2011) for *P. pinea* in the same area. Also, Calama et al. (2011) observed a negative effect of the number of days with severe frost during the first winter after cone initiation. Interestingly, we found that the higher the minimum temperature in October of the first year was, the lower the predicted number of seeds was."(Ruano et al.2015b)
Pinus radiata	Monterey	"*Pinus radiata* is also moderately cold hardy, but less so than *P. greggii* var. *australis*." (Hodge 2012)

Species	Common	Cold hardiness
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	[…] a significant degree of cold hardiness was maintained. (Hawkins 2003) Doulas fir (*Psuedotsuga menziesii*) < mountain hemlock (*Tsuga mertensiana*), true firs (*Abies* spp.), Engelmann spruce (*Picea engelmannii*), western white pine (*Pinus monticola*), and lodgepole pine (*Pinus contorta*). (Burns and Honkala 1990) "Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." (Ledgard and Baker 1988)
Larix decidua	European larch	"Amongst the introduced species the conifers excelled, the best on depleted sites being lodgepole pine (*Pinus contorta* -- approximate altitudinal limit, 1400m), the mountain pines (*P. mugo* and *P. uncinata* -- 1600m) Scots pine (*P. sylvestris* -- 1250m), ponderosa pine (*P. ponderosa* -- 1150m) and Corsican pine (*P. nigra* - 1100m). On the more favourable slopes Douglas fir (*Pseudotsuga menziesii* --1300) and European larch (*Larix decidua* - 1100m) performed well." (Ledgard and Baker 1988)
Larix laricina	tamarack	
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	
Sequoiadendron giganteum	Giant redwood	"Low temperatures seem to be a limiting factor for giant sequoia at the upper elevational limits of its range, as well as in areas with severe winters where the species has been introduced." (Burns and Honkala 1990)
Picea abies	Norway spruce	
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	

Species	Common	Cold hardiness
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	
Thuja plicata	western red cedar	[…] a significant degree of cold hardiness was maintained. (Hawkins 2003)
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

S15. Drought tolerance

Species	Common	Drought tolerance
Pinus contorta	lodgepole	"Drought is a leading factor in the loss of lodgepole pine seedlings during the dry summers of the Rocky Mountains. Roots produced by the seedlings penetrate only 10±15 cm into the soil during the first year (Noble, 1979) and lateral roots spread horizontally instead of downward (Preston, 1942). If rainfall is not sufficient to keep the upper 15 cm of soil wet, the seedlings die. Where extended rainless periods are not common during the growing season, this would be of minor concern. By the second year, the roots usually penetrate deep enough into the soil to find enough water to survive longer rainless periods. A greenhouse study of precipitation effects (Sheppard and Noble, 1976) showed that less than 5 cm per month greatly reduced germination. Field experience reinforces this observation (Lotan and Perry, 1983). Distribution of monthly precipitation and soil factors that affect water-holding capacity also are important" (Despain 2001) drought: tolerant (Timmins and Mackenzie 1995)
Pinus sylvestris	Scots	"It grows in areas with an annual precipitation exceeding 1780 mm (70 in) and in areas with an annual precipitation as little as 200 mm (8 in)." (Burns and Honkala 1990) "Water availability during the summer seems to be the key factor driving *P. sylvestris* regeneration at Sierra de Guadarrama, similarly to what has been recorded at its southernmost distribution limit (Matias and Jump, 2014)." (Calama et al.2017) "We determined photosynthesis, biomass distribution, root and rhizosphere respiration, water potential, leaf osmolalities and carbon and nitrogen assimilation patterns in both treatments. The photosynthetic rate of the drought-induced seedlings did not decrease compared to the control group, the maximum leaf specific photosynthetic rate being 0.058 and 0.045 µmol g-1 s-1 for the drought and control treatments, respectively. The effects of drought were, however, observed as lower water potentials, increased osmolalities as well as decreased growth and greater fine root-to-shoot ratio in the drought-treated seedlings. We also observed improved uptake of labelled nitrogen from soil to needles in the drought-treated seedlings. The results indicate acclimation of seedlings to long-term drought by aiming to retain sufficient water uptake with adequate allocation to roots and root-associated mycorrhizal fungi. The plants seem to control water potential with osmolysis, for which sufficient photosynthetic capability is needed." (Aaltonen et al.2017) "At the end of the study period in September, between 8 and 29 % of the seedlings had stems which were desiccated to more than 75 % (Fig. 6). On average, further 27 ± 7 % of the seedlings per plot had drought-related damage that extended to 25–75 % of the stem surface. There was no consistent trend across steppe community or in irrigated versus non-irrigated plots" (Dulamsuren et al.2013) "Results from the repeated measurements analysis of variance showed a significant effect of drought on survival over time ($p < 0.0001$). Irrespective of the age of the mother tree, seedlings showed a survival rate of over 90% during 113 days after watering was interrupted, even if, by then, soil moisture had already reached 0% (Figure 4). From this day, survival drastically decreased to 27.1% in a week, although some seedlings remained still alive for another 47 days until the end of the experiment (day 160)." (Pardos et al.2022)

Species	Common	Drought tolerance
Pinus mugo complex	mountain	
Pinus nigra	black, Austrian	"Annual precipitation varies from 610 to 1020 mm (24 to 40 in" (Burns and Honkala 1990) drought: tolerant (Timmins and Mackenzie 1995)
Pinus ponderosa	Ponderosa	"In Montana, east of the Continental Divide, average annual precipitation in ponderosa pine forests ranges from 280 to 430 mm (11 to 17 in), with 125 to 250 mm (5 to 10 in) received during the May-to-August period" (Burns and Honkala 1990) "Ponderosa pine has the capacity for root growth in relatively dry soil. Nursery stock lifted in January in California had appreciable root elongation even when planted in soil with a water potential of less than -0.9 MPa (-9 bars) and has survived, at least for short periods, water potentials of less than -8.0 MPa (-80 bars) in the Southwest." (Burns and Honkala 1990) "*P. ponderosa* has self-established prolifically in a 400-600 mm annual rainfall environment in Central Otago (Douglas 1970), yet it is also sparsely naturalised under a 4000 mm annual rainfall in the Hooker Valley near Mount Cook (Urilson, 1976)" (Hunter and Douglas 1984) "drought was the primary cause of mortality at all watering levels" (Shepperd et al.1976)
Pinus muricata	bishop	
Pinus pinaster	maritime	Primary cone growth was limited by extreme cold events. Absence of precipitation limits secondary growth and hinders final cone ripening. It turns out that seed production and seed rain may be a bottleneck for natural regeneration of P. pinaster under low stand densities, especially under extreme climatic scenarios (Ruano et al.2015b) We can confirm our first hypothesis of a climate-mediated interannual seed production pattern. Specifically, all considered explanatory variables were exclusively related to cone growth and maturation. Rodríguez-Soalleiro et al. (2008) asserted that flowering in *P. pinaster* is affected by light, temperature, precipitation, and drought. We tested the effects of precipitation, wind velocity, and frost as potential surrogates, but none of them was found to be significant in our analysis. Similarly, we did not find any association between climatic variables and seed rain. Apparently, high temperatures may favour cone opening (Nathan et al. 1999; Tapias et al. 2001), although this may refer to serotinous species, and the local provenance of this study is weakly serotinous. (Ruano et al.2015b) "The positive effect of precipitation during the period of secondary cone growth points out that water stress is a limiting factor for seed production in P. pinaster in the Castilian Plateau. These findings coincide with those of Mutke et al. (2005) and Calama et al. (2011) for *P. pinea* in the same area. Also, Calama et al. (2011) observed a negative effect of the number of days with severe frost during the first winter after cone initiation. Interestingly, we found that the higher the minimum temperature in October of the first year was, the lower the predicted number of seeds was." (Ruano et al.2015b)

Species	Common	Drought tolerance
		drought: tolerant (Timmins and Mackenzie 1995)
Pinus radiata	Monterey	"Drought tolerant " (Timmins and Mackenzie 1995)
Pinus x attenuata	knobcone	
Pseudotsuga menziesii	Douglas fir	annual precipitation 360 to 3050 mm (Burns and Honkala 1990) Doulas fir (*Psuedotsuga menziesii*) < ponderosa pine (*P. ponderosa*) (Burns and Honkala 1990) "drought intolerant " (Timmins and Mackenzie 1995) "Until the roots have penetrated deeply there is a risk of death from summer droughts. In any case, like many temperate species Douglas-fir has almost zero growth during the shorter days of winter and relies greatly on summer rainfall. The odd tree might survive in drier locations, and there are certainly long dry seasons in parts of its natural habitat, but the fact remains that volume yield is directly proportional to water availability during the growing season. Water does not necessarily relate to precipitation because some soils can retain sufficient moisture to tide the tree over prolonged periods of low rainfall, or thanks to deep root penetration allow access to reliable supplies of groundwater" (Maclaren et al.2009)
Larix decidua	European larch	drought: slightly intolerant (Timmins and Mackenzie 1995)
Larix laricina	tamarack	"Because they are small, tamarack seedlings are easily killed during the first 6 or 8 weeks after germination. Early losses are primarily caused by damping-off; in the second and third years drought, drowning, and inadequate light sometimes cause appreciable loss. One-year-old seedlings grown in full light can survive desiccation of the upper 2 to 3 cm (1 in) of organic soils to as low as 45 to 65 percent by weight, whereas forest-grown seedlings 1 to 3 years old are fairly intolerant of drought (or flooding)" (Burns and Honkala 1990)
Larix occidentalis	western larch	
Sequoia sempervirens	Coastal redwood	"Annual precipitation varies between 640 and 3100 mm... and is mostly winter rain" (Burns and Honkala 1990) "New redwood seedlings require a greater supply of soil moisture for survival than that needed by seedlings of most associated trees." (Burns and Honkala 1990) "Consequently, redwood roots do not seem to function efficiently in extracting soil moisture. This fact may limit natural distribution to sites where favorable water relations result from high rainfall, humid air, moist soil, or low summer temperatures, or from various combinations of these conditions." (Burns and Honkala 1990)
Sequoiadendron giganteum	Giant redwood	"Mean annual precipitation in the groves varies from about 900 to 1400 mm" (Burns and Honkala 1990) "Distribution of the species at low elevations is limited mainly by deficient soil moisture during the growing season" (Burns and Honkala 1990)

Species	Common	Drought tolerance
Picea abies	Norway spruce	
Picea engelmannii	Engelmann spruce	
Picea sitchensis	Sitka spruce	
Abies grandis	grand fir	
Cupressus macrocarpa	macrocarpa	
Hesperocyparis lusitanica	Mexican cypress	
Chamaecyparis lawsoniana	Lawson's cypress, Port-Orford-Cedar	"Drought damages native trees on the hotter sites and in inland areas without seepage. Port-Orford-cedar is more affected than its associates on these sites." (Burns and Honkala 1990)
Thuja plicata	western red cedar	
Cryptomeria japonica	Sugi, Japanese cedar	
Cedrus deodara	Deodar cedar	

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