Article	Category	Abstract / Summary
Bansal, S., St. Claire, J., Harrington C, Gould P. Impact of climate change on cold hardiness of Douglas-fir Pseudotsuga menziesii): environmental and genetic considerations. Global Change Biology · April 2015	Climate change	The success of conifers over much of the world's terrestrial surface is largely attributable to their tolerance to cold stress (i.e., cold hardiness). Due to an increase in climate variability, climate change may reduce conifer cold hardiness, which in turn could impact ecosystem functioning and productivity in conifer-dominated forests. The expression of cold hardiness is a product of environmental cues (E), genetic differentiation (G), and their interaction (G 9 E), although few studies have considered all components together. To better understand and manage for the impacts of climate change on conifer cold hardiness, we conducted a common garden experiment replicated in three test environments (cool, moderate, and warm) using 35 populations of coast Douglas-fir (Pseudotsuga menziesii var. menziesii) to test the hypotheses: (i) cool-temperature cues in fall are necessary to trigger cold hardening, (ii) there is large genetic variation among populations in cold hardiness that can be predicted from seed-source climate variables, (iii) observed differences among populations in cold hardiness in situ are dependent on effective environmental cues, and (iv) movement of seed sources from warmer to cooler climates will increase risk to cold injury. During fall 2012, we visually assessed cold damage of bud, needle, and stem tissues following artificial freeze tests. Cool-temperature cues (e.g., degree hours below 2 °C) at the test sites were associated with cold hardening, which were minimal at the mod-erate test site owing to mild fall temperatures. Populations differed 3-fold in cold hardiness, with winter minimum temperatures and fall frost dates as strong seed-source climate predictors of cold hardiness, and with summer tem-peratures and aridity as secondary predictors. Seed-source movement resulted in only modest increases in cold damage. Our findings indicate that increased fall temperatures delay cold hardening, warmer/drier summers confer a degree of cold hardiness, and seed-source movement from warmer to cooler climates may be a viable option for adapting coniferous forest to future climate.
MacLachlan, I. Wang, T., Hamann, A., Smets, P., Aitken, S. (2017), Selective breeding of lodgepole pine increases growth and maintains climatic adaptation. Forest Ecology and Management 391 (2017) 404-416	Climate change	Climate change is disrupting historical patterns of adaptation in temperate and boreal tree species, causing local populations to become maladapted. Tree improvement programs typically utilise local base pop-ulations and manage adaptation using geographically defined breeding zones. As climates shift, breeding zones are no longer optimal seed deployment zones because base populations are becoming dissociated rom their historical climatic optima. In response, climate-based seed transfer (CBST) policies incorporat- ing assisted gene flow (AGF) are being adopted to pre-emptively match reforestation seedlots with future climates, but their implementation requires accurate knowledge of genetic variation in climatically adap- tive traits. Here we use lodgepole pine as a case study to evaluate the effects of selective conifer breeding on adaptive traits and their climatic associations to inform CBST and AGF prescriptions. Our approach compared 105 natural stand and 20 selectively bred lodgepole pine seedlots from Alberta and British Columbia grown in a common garden of 2200 seedlings. The effects of selection on pheno- typic variation and climatic associations among breeding zones were assessed for growth, phenology and cold hardiness. We found substantial differences between natural and selected seedlings in growth traits, but timing of growth initiation was unaffected, growth cessation was delayed slightly (average 4 days, range 0.7 days to 10 days), and cold injury was slightly greater (average 2.5%, range 7% to 11%) in selected seedlings. Phenotypic differentiation among breeding zones and climatic clines were stronger for all traits in selected seedlings. Height gains resulted from both increased growth rate and delayed growth cessation, but negative indirect effects of selection on cold hardiness were weak. Selection, breeding and progeny testing combined have produced taller lodgepole pine seedlings that are not adaptively compromised relative to their natural seedling counterparts. Selective breeding pro-duces genotypes that achieve increased height growth and maintain climate adaptation, rather than reconstituting genotypes similar to populations adapted to warmer climates. While CBST is needed to optimise seedlot deployment in new climates, an absence of systematic indirect selection effects on adap- tive traits suggests natural and selected seedlots do not require separate AGF prescriptions.
Allen, C., Breshears, D., & McDowell, N. (2015). On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere, 6(8), 1–55	Climate change	Patterns, mechanisms, projections, and consequences of tree mortality and associated broadscale forest die-off due to drought accompanied by warmer temperatures-"hotter drought", an emerging characteristic of the Anthropocene-are the focus of rapidly expanding literature. Despite recent observational, experimental, and modeling studies suggesting increased vulnerability of trees to hotter drought and associated pests and pathogens, substantial debate remains among research, management and policy-making communities regarding future tree mortality risks. We summarize key mortality-relevant findings, differentiating between those implying lesser versus greater levels of vulnerability. Evidence suggesting lesser vulnerability includes forest benefits of elevated [CO 2] and increased water-use efficiency; observed and modeled increases in forest growth and canopy greening; widespread increases in woody-plant biomass, density, and extent; compensatory physiological, morphological, and genetic mechanisms; dampening ecological feedbacks; and potential mitigation by forest management. In contrast, recent studies document more rapid mortality under hotter drought due to negative tree physiological responses and accelerated biotic attacks. Additional evidence suggesting greater vulnerability includes rising background mortality rates; projected increases in drought frequency, intensity, and duration; limitations of vegetation models such as inadequately represented mortality processes; warming feedbacks from die-off; and wildfire synergies. Grouping these findings we identify ten contrasting perspectives that shape the vulnerability debate but have not been discussed collectively. We also present a set of global vulnerability drivers that are known with high confidence: (1) droughts eventually occur everywhere; (2) warming produces hotter droughts; (3) atmospheric moisture demand increases nonlinearly with temperature during drought; (4) mortality can occur faster in hotter drought, consistent with fundamental physiology; (5) shorter droughts occur more frequently than longer droughts and can become lethal under warming, increasing the frequency of lethal drought nonlinearly; and (6) mortality happens rapidly relative to growth intervals needed for forest recovery. These high-confidence drivers, in concert with research supporting greater vulnerability perspectives, support an overall viewpoint of greater forest vulnerability globally. We surmise that mortality vulnerability is being discounted in part due to difficulties in predicting threshold responses to extreme climate events. Given the profound ecological and societal implications of underestimating global vulnerability to hotter drought, we highlight urgent challenges for research, management, and policy-making communities

Allen, C., Macalady, A., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., … Cobb, N. (2009). A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management, 259(4), 660–684	Climate change	Greenhouse gas emissions have significantly altered global climate, and will continue to do so in the future. Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate change could fundamentally alter the composition, structure, and biogeography of forests in many regions. Of particular concern are potential increases in tree mortality associated with climate-induced physiological stress and interactions with other climate-mediated processes such as insect outbreaks and wildfire. Despite this risk, existing projections of tree mortality are based on models that lack functionally realistic mortality mechanisms, and there has been no attempt to track observations of climate-driven tree mortality globally. Here we present the first global assessment of recent tree mortality attributed to drought and heat stress. Although episodic mortality occurs in the absence of climate change, studies compiled here suggest that at least some of the world's forested ecosystems already may be responding to climate change and raise concern that forests may become increasingly vulnerable to higher background tree mortality rates and die-off in response to future warming and drought, even in environments that are not normally considered water-limited. This further suggests risks to ecosystem services, including the loss of sequestered forest carbon and associated atmospheric feedbacks. Our review also identifies key information gaps and scientific uncertainties that currently hinder our ability to predict tree mortality in response to climate change and emphasizes the need for a globally coordinated observation system. Our review reveals the potential for amplified tree mortality due to drought and heat in forests worldwide.
Davis, K., Dobrowski, S., Higuera, P., Holden, Z., Veblen, T., Rother, M., … Maneta, M. (2019). Wildfires and climate change push low-elevation forests across a critical climate threshold for tree regeneration. Proceedings of the National Academy of Sciences of the United States of America, 116(13), 6193–6198	Climate change	Climate change is increasing fire activity in the western United States, which has the potential to accelerate climate-induced shifts in vegetation communities. Wildfire can catalyze vegetation change by killing adult trees that could otherwise persist in climate conditions no longer suitable for seedling establishment and survival. Recently documented declines in postfire conifer recruitment in thewestern United States may be an example of this phenomenon. However, the role of annual climate variation and its interaction with long-term climate trends in driving these changes is poorly resolved. Here we examine the relationship between annual climate and postfire tree regeneration of two dominant, low-elevation conifers (ponderosa pine and Douglas-fir) using annually resolved establishment dates from 2,935 destructively sampled trees from 33 wildfires across four regions in the western United States. We show that regeneration had a nonlinear response to annual climate conditions, with distinct thresholds for recruitment based on vapor pressure deficit, soil moisture, and maximum surface temperature. At dry sites across our study region, seasonal to annual climate conditions over the past 20 years have crossed these thresholds, such that conditions have become increasingly unsuitable for regeneration. High fire severity and low seed availability further reduced the probability of postfire regeneration. Together, our results demonstrate that climate change combined with high severity fire is leading to increasingly fewer opportunities for seedlings to establish after wildfires and may lead to ecosystem transitions in low-elevation ponderosa pine and Douglas-fir forests across the western United States.
Kemp, K., Higuera, P., Morgan, P., & Abatzoglou, J. (2019). Climate will increasingly determine post-fire tree regeneration success in low-elevation forests, Northern Rockies, USA. Ecosphere, 10(1), e02568 (1-17).	Climate change	Climate change is expected to cause widespread shifts in the distribution and abundance of plant species through direct impacts on mortality, regeneration, and survival. At landscape scales, climate impacts will be strongly mediated by disturbances, such as wildfire, which catalyze shifts in species distributions through widespread mortality and by shaping the post-disturbance environment. We examined the potential for regional shifts in low-elevation tree species in response to wildfire and climate warming in low-elevation, dry mixed-conifer forests of the northern Rocky Mountains, USA. We analyzed interactions among climate and wildfire on post-fire tree seedling regeneration 5–13 yr post-fire at 177 sites burned in 21 large wildfires during two years with widespread regional burning. We used generalized additive mixed models to quantify how the density of Douglas-fir and ponderosa pine seedlings varied as a function of climate normals (30-yr mean temperature, precipitation, soil moisture, and evapotranspiration) and fire (tree survivorship, burn severity, and seed source availability). Mean summer temperature was the most important predictor of post-fire seedling densities for both ponderosa pine and Douglas-fir. Seed availability was also important in determining Douglas-fir regeneration. As mean summer temperature continues to increase, however, seed availability will become less important for determining post-fire regeneration. Above a mean summer temperature of 17°C, Douglas-fir regeneration is predicted to be minimal regardless of how close a seed source is to a site. The majority (82%) of our sampled sites are predicted to exceed a mean summer temperature of 17°C by mid-century, suggesting significant declines in seedling densities and potential forest loss. Our results highlight mechanisms linking climate change to shifts in the distribution of two widely dominant tree species in western North America. Under a warming climate, we expect post-fire tree regeneration in these low-elevation forests to become increasingly unsuccessful. Such widespread regeneration failures would have important implications for ecosystem processes and forest resilience, particularly as wildfires increase in response to climate warming.
Simeone, C., Maneta, M., Holden, Z., Sapes, G., Sala, A., & Dobrowski, S. (2019). Coupled ecohydrology and plant hydraulics modeling predicts ponderosa pine seedling mortality and lower treeline in the US Northern Rocky Mountains. New Phytol, 221, 1814–1830.	Climate change	We modeled hydraulic stress in ponderosa pine seedlings at multiple scales to examine its influence on mortality and forest extent at the lower treeline in the northern Rockies. We combined a mechanistic ecohydrologic model with a vegetation dynamic stress index incorporating intensity, duration and frequency of hydraulic stress events, to examine mortality from loss of hydraulic conductivity. We calibrated our model using a glasshouse dry-down experiment and tested it using in situ monitoring data on seedling mortality from reforestation efforts. We then simulated hydraulic stress and mortality in seedlings within the Bitterroot River watershed of Montana. We show that cumulative hydraulic stress, its legacy and its consequences for mortality are predictable and can be modeled at local to landscape scales. We demonstrate that topographic controls on the distribution and availability of water and energy drive spatial patterns of hydraulic stress. Low-elevation, south-facing, nonconvergent locations with limited upslope water subsidies experienced the highest rates of modeled mortality. Simulated mortality in seedlings from 2001 to 2015 correlated with the current distribution of forest cover near the lower treeline, suggesting that hydraulic stress limits recruitment and ultimately constrains the low-elevation extent of conifer forests within the region.

Aitken, Sally & Adams, W.T.. (2011). Genetics of fall and winter cold hardiness of coastal Douglas-fir in Oregon. Canadian Journal of Forest Research. 26. 1828-1837. 10.1139/x26-208.	Genetics - Frost	Genetic variation in fall cold hardiness was studied in two western Oregon breeding populations of coastal Douglas-fir (Pseudotsuga menziesii var. menziesii (Mirb.) Franco), one on the west slope of the Cascade Mountains and the other in the Coast Range. On six sampling dates (September, October, and November of 1992 and January, September, and October of 1993), shoot cuttings from 40 open-pollinated families in each of two progeny test sites for each breeding zone were subjected to artificial freezing at two test temperatures. Damage on each shoot was recorded as visible injury to needle, stem, and bud tissues separately. Considerable family variation was found for cold injury scores in all tissues in early fall to mid fall, but differences were often smaller or nonsignificant in late fall and midwinter. Individual heritability estimates for needle cold injury were low (<0.40) and generally decreased in late fall and midwinter. Family rankings for fall cold hardiness, however, are expected to be relatively consistent over sites and years, although needles appear to display more family-by-site interaction than stems or buds. Genetic correlations between tissues in cold injury varied considerably and were sometimes weak, indicating that the evaluation of a single tissue is probably not adequate for assessing overall cold hardiness of genotypes. Fall and winter cold hardiness seem to be largely under separate genetic control since genetic correlations between hardiness at these two stages were weak. This study confirms earlier results in Washington breeding populations and shows that coastal Douglas-fir families can be effectively ranked for fall cold hardiness by conducting artificial freeze tests on cut shoots in (October) and scoring damage to stems and at least one other tissue.
Hannerz, M., Aitken, S., King, K.,, and Budge S. (1999). Effects of genetic selection for growth on frost hardiness in western hemlock. Can. J. For. Res. 29: 509–516 (1999)	Genetics - Frost	Fall and spring frost hardiness was determined from electrolytic leakage of artificially frozen needle segments in 22 full-sib families of western hemlock (Tsuga heterophylla (Raf.) Sarg.) from British Columbia and Washington State representing different levels of genetic gain, and of four provenance materials (stand progenies from the Queen Charlotte Islands, Vancouver Island, and Oregon Cascades, and seed-orchard progenies from the northern Oregon Coast Range). Samples for freeze testing were collected in a 5-year-old trial at Jordan River on southwestern Vancouver Island. Height and date of bud flush were recorded in the field. Genetic gain among the full-sib families was not correlated with fall frost hardiness, but high-yielding families displayed a lower spring frost hardiness and an earlier bud flush than low-yielding families. Both fall and spring frost hardiness increased and height growth decreased with the latitude of provenances. The highest growth, earliest bud flush and lowest fall and spring frost hardiness was demonstrated by the Oregon provenances, while the lowest growth, latest bud flush and highest hardiness was found for the Queen Charlotte Islands provenance.
Montwé, D., Isaac-Renton, M., Hamann, A. et al. Cold adaptation recorded in tree rings highlights risks associated with climate change and assisted migration. Nat Commun 9, 1574 (2018). https://doi.org/10.1038/s41467-018-04039-5	Genetics - Frost	With lengthening growing seasons but increased temperature variability under climate change, frost damage to plants may remain a risk and could be exacerbated by poleward planting of warm-adapted seed sources. Here, we study cold adaptation of tree populations in a wide-ranging coniferous species in western North America to inform limits to seed transfer. Using tree-ring signatures of cold damage from common garden trials designed to study genetic population differentiation, we find opposing geographic clines for spring frost and fall frost damage. Provenances from northern regions are sensitive to spring frosts, while the more productive provenances from central and southern regions are more susceptible to fall frosts. Transferring the southern, warm-adapted genotypes northward causes a significant loss of growth and a permanent rank change after a spring frost event. We conclude that cold adaptation should remain an important consideration when implementing seed transfers designed to mitigate harmful effects of climate change.
Hawkins B.J., Stoehr (2009) Growth, phenology, and cold hardiness of 32 Douglas-fir full-sib families. Can. J. For. Res. 39: 1821–1834 (2009)	Genetics - Frost	Thirty-two full-sib families of coastal Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco var. menziesii) with a range of predicted breeding values were monitored for growth rate, phenology, and cold hardiness over 2 years on two sites to investigate if other traits are being selected when family selection is based on height. Significant differences among families existed in most phenological, growth, and cold-hardiness traits. On average, taller families burst bud later but did not have significantly different growth rates or length of growing period than other families. We found no signifi-cant correlations between family date of bud burst and cold hardiness in late spring or between duration of shoot growth or height and autumn freezing damage. Family differences in freezing tolerance were greatest in September and October. In these months, family current-year leaf nitrogen was positively correlated with cold hardiness. Families that were most hardy in the autumn were not the most hardy families in spring. We conclude that, for the studied breeding series, selec- tion based on height does not have a significant impact on cold hardiness. We found no consistent relationships between phenological, growth, or cold-hardiness parameters and final height that could explain family ranking by height. Relation- ships between grandparent elevation and dates of bud burst and cold hardiness were observed.

Cariboo-Chilcotin Land-Use Plan. 2005. Williams Lake Sustainable Sustainable Resource Management Plan. Williams Lake. Available from https://www2.gov.bc.ca/gov/content/industry/crown-land-water/land-use-planning/regions/cariboo/cariboochilcotin-rlup	Management	The Cariboo-Chilcotin Land Use Plan (CCLUP), announced by the B.C. government in 1994, establishes the long-term balance of environment and economy in the Cariboo-Chilcoltin region. The plan provides for: Access to timber for the local forest industry Certainty for mining, ranching and tourism industries Conservation and recreation objectives for natural values Economic and social stability Increased opportunities for growth and investment throughout the region The CCLUP was designated as a higher level plan in 1996 under the Forest Practices Code of British Columbia Act (FPC), and guided the application of the Code and other resource management activities within the plan area. The resource management objectives, targets and strategies within the CCLUP were carried forward under the Land Act as objectives under the Forest and Range Practices Act (FRPA) which replaced the FPC in 2002. A key part of implementing the CCLUP was the completion of seven sustainable resource management plans (SRMPs) covering the entire Cariboo Region. These plans were completed by 2007, and address CCLUP strategies and targets on an area-specific basis through detailed objectives and strategies for the management of natural resources and the maintenance of environmental values. They were endorsed by government and resource stakeholders and remain as non-legal guidance. Using the SRMPs as a foundation, a Land Use Objectives Order (LUO) was declared under the Land Use Objectives Regulation under the Land Act in 2010, which sets legal direction for forestry activities under FRPA with respect to key resource values. The order contains objectives and maps for biodiversity, wildlife trees, old growth forest, critical habitat for fish, community areas of special concern, lakes, riparian areas, mature birch retention, grasslands, scenic areas, recreation trails, high value wetlands for moose, and grizzly bear. An additional element of implementing the CCLUP was the completion of wildlife management strategies, which between 2001 and 2010 resulted in the approval of orders under the Government Action Regulation under FRPA for management requirements for mule deer, caribou and other wildlife species.
Cariboo-Chilcotin Land-Use Plan Mule Deer Strategy Committee. 2014. Regional Mule Deer Winter Range Strategy. In Cariboo-Chilcotin Land Use Plan. Information Note #2. Ministry of Forests, Lands and Natural Resource Operations. Available from https://www2.gov.bc.ca/gov/content/industry/crown-land-water/land-use-planning/regions/cariboo/cariboochilcotin-rlup	Management	The Cariboo-Chilcotin land use plan management strategy for mule deer winter ranges in the Cariboo-Chilcotin is designed to guide forest harvest planning to restore and maintain mule deer winter range habitat suitability. The strategy provides practical direction for planning and practices at both the landscape and stand levels to integrate mule deer habitat values with industrial timber development. The CCLUP Integration Report mandated the creation of the Cariboo Regional mule deer winter range committee, comprised of ministry resource experts, to develop mule deer winter range plans and objectives.
Spittlehouse, D.L. and R.J. Stathers. 1990. Seedling microclimate. B.C. Ministry of Forests, Victoria, B.C. Land Management Report No. 65.	MSP	The microclimate has a significant influence on the survival and growth of seedlings. Microclimate is affected by macroclimate, site, vegetation and soil factors. The influence of these factors on the light, precipitation, humidity, wind, air temperature, soil moisture and soil temperature regimes of the seedling is explained. Examples of how site preparation can modify microclimate are presented.
Hope, G.D. 1991. Effects of mechanical site preparation on soil and foliar nu-trients in the drier subzones of the IDF, MS and ESSF zones: project 3.50. Forestry Canada and B.C. Ministry of Forests, Victoria, B.C. FRDA Research Memo No. 193.	MSP	Many of the mechanical site preparation techniques used in the dry subzones of the southern Interior involve the displace-ment of surface organic layers, which leaves a bare mineral soil surface into which the crop seedling is planted, Recent research has shown the advantages of these methods of site preparation in reducing both frost damage and vegetation competition, while at the same time increasing moisture availability, Few studies, however, have investigated how the removal of nutrient-and organic matter-rich materials from the forest floor might affect crop tree nutrition. This project addressed the question by evaluating the effects of forest floor removal, during mechanical site preparation, on soil and foliar nutrients.
Newsome, T.A., J.L. Heineman, and A.F.L. Nemec. 2016. Long-term results from EP841: Douglas-fir, lodgepole pine, and hybrid spruce responses to mechanical site preparation in the Interior Douglas-fir and Sub-Boreal Spruce Zones of South-central British Columbia. Prov. B.C., Victoria, B.C. Tech. Rep. 092.	MSP	In 1982, a large-scale experimental project (EP841) was initiated in the Cariboo Region of south-central British Columbia, which is climatically transitional between the northern and southern portions of the province and thus features a wide diversity of climatic and site conditions. This project includes four individual site preparation studies and experimental installations on 10 sites. The potential of scalping, ripping, plowing, and trenching techniques to improve planted conifer seedling survival and growth outcomes were examined in the dry, cool Interior Douglas-fir (IDF) and dry, warm Sub-Boreal Spruce (SBS) biogeoclimatic zones. Although some installations included hybrid spruce and ponderosa pine, the project's primary focus was on survival and early growth of Douglas-fir and lodgepole pine. It sheds light on plantation management issues that are currently important in both zones. This study demonstrates that site preparation is a useful tool for improving survival of planted Douglas-fir in both the SBSdw and dry IDF subzone/variants. Especially in the SBSdw, the positive outcomes contradict the belief that establishing planted Douglas-fir is an insurmountable challenge. Given the extent to which lodgepole pine has dominated regeneration programs in the Central Interior during the past three decades and our increasing awareness of health problems affecting this species, encouraging Douglas-fir establishment is highly desirable. Although the IDF is clearly a more challenging regeneration proposition than the SBSdw, the use of an appropriate site preparation technique in combination with cattle management resulted in at least moderate Douglas-fir survival on the majority of sites examined in the EP841 experiments. Overall, the encouraging survival responses of Douglas-fir to site preparation were the most important findings of this project.

Waterhouse, M. 1998 Natural Regeneration in Managed Uneven-aged Douglas-fir Stands in the IDFdk3, IDFxm and IDFxw Biogeoclimatic Subzones. BC MOF Cariboo Forest Region Research Extension Note #24	Natural regeneration	Uneven-aged drybelt interior Douglas-fir (Pseudotsuga menziesii var. glauca) stands have been harvested for over 50 years in British Columbia. Within the Cariboo Forest Region, most drybelt Douglas-fir stands are located in the Interior Douglas-fir (IDF) biogeoclimatic zone. Stands have been partially cut at varying intensities. Natural shelterwoods, based on cutting all trees over a fixed diameter, were common through the 1970's to the mid-1980's. This was replaced by the single tree selection silviculture system to improve the quality of the residual stand, decrease logging damage and improve regeneration establishment on dry sites after harvest. Despite the number of years in which drybelt uneven-aged Douglas-fir stands have been harvested, very little information is available on post-harvest natural regeneration success and stand basal area growth rates. In 1995, a retrospective study was initiated to increase understanding of how past harvesting practices have effected natural regeneration establishment and growth within uneven aged Douglas-fir stands. Stands were selected in three subzones: IDFdk3, IDFxm and IDFxw. All 31 stands in the study were partially cut between 1980 and 1987, but not spaced. This extension note summarizes the results from two unpublished reports (Catton 1997; Day 1996). For clarification, the authors define Stocking as a measure of site occupancy and is described by basal area, and Density as a measure of spacing, or competition and is described by stems/ha. CONCLUSIONS · there is sufficient natural regeneration regardless of harvesting intensity with one exception - steep, southerly slopes with low crown closure.· juvenile spacing is required to improve growth and maintain density control · basal area growth needs to accumulate on larger size trees therefore prescriptions have to leave adequate numbers of larger trees on the block by adjusting residual growing stock (B), maximum diameter (D) and quotients of dimunition (q). · IDF Douglas-fir stands are highly variable in terms of pre-harvest stand structure - therefore prescriptions need to be site specific and carefully applied.
Newsome, T.A. 1993. Improving Douglas-fir Survival and Growth by Planting under a Stand of Juvenile Lodgepole Pine. B.C. Min. For., Cariboo For. Reg. Exten. Note 06.	Nurse species	Douglas-fir is the dominant climax species in the Interior Douglas-fir (IDF) subzone, and forests are highly-valued for a multiple of resource uses, such as timber, range, recreation, aesthetics and wildlife habitat. As a moderately shade tolerant species in the IDF subzones, Douglas-fir does not grow well in open conditions - clearcuts or old wildfires - where there is increased light, diurnal extremes in air temperature, and frequent summer drought. Summer frost is the major limiting factor to acceptable survival and growth of fir on these IDF sites. On moister sites in the ICH and SBS subzones, fir is a productive seral species with less need for shade. Planting under pine provides suitable conditions for Douglas-fir seedling survival in the dry subzones (IDFdk3, IDFdk4 and SBSdw1) by reducing the severity of summer frosts and providing shade. However, this option for regenerating Douglas-fir must be cautiously considered. The pine provides cover for snowshoe hares and other wildlife, which may have a negative impact on seedling survival and growth. As well, a stocked pine stand does not appear to provide suitable conditions for seedling growth. Wider-spaced pine overstories may be more suitable.
Daintith N., T.A. Newsome, and A. Lacourciere. 1995. Effect of screefing and V-plow site preparation on seedling survival and growth in areas of heavy grass competition: ten year results. (SX84503) B.C. Ministry of Forests, Cariboo Forest Region, Williams Lake, B.C. Unpublished report.	Seedling survival	
Black, A. 1990. Effects of Site Preparation Treatments on the Soil Moisture Regime in IDFdk, MSxk and ESSFxc Clearcuts - Project 3.02 Forestry Canada and B.C. Ministry of Forests, Victoria, B.C. FRDA Research Memo No 162	Seedling survival	This memo reports the results of research conducted during 1986 to 1989 into the effects of site preparation on the soil moisture regime in the IDFdk, MSxk and ESSFxc clearcuts. The scalping, ripping, and herbicide treatments all effectively conserved soil water at all field sites. Low soil moisture reduced seedling growth in the control at the IDFdk site in all four years of the research. As a results of water conservation seedlings in the treated plots showed virtually no growth limitation due to low soil moisture content.
Daintith, N.M. and T.A. Newsome. 1996. Effect of Mechanical Site Preparation and Fencing on Five-Year Growth of Douglas-Fir and Lodgepole Pine Seedlings Planted on Dry Sites in the Cariboo Forest Region. Res. Br., B.C. Min. For. and For. Can., Victoria, B.C. FRDA Rep. 252	Seedling survival - Cattle	
Nicholson, A. 1989. Water relations, survival and growth of Douglas-fir seedlings at a pinegrass-dominated site in south-central British Columbia. Forestry Canada and B.C. Ministry of Forests, Victoria, B.C. FRDA Research Memo No. 121.	Seedling survival - Drought	This study examined the effects of pinegrass and several environmental factors on the survival and performance of Douglas-fir seedlings. The study site was a pinegrass dominated clearcut in the IDFdk subzone approximately 50km south of Williams Lake. The major conclusion and underlying theme is that the high rate of morality of planted Douglas-fir seedlings is the result of a combination of several factors including: drought, spring frost, poor vigour at the time of planting and animal damage. Furthermore, pinegrass competition appears to exacerbate seedling moisture stress. In this memo I discuss several implications of the results to silviculture practices.
Newsome, T. 1998. Site Preparation on Dry Grassy Sites in the Cariboo Forest Region. In Managing the Dry Douglas-fir Forests of the Southern Interior: Workshop Proceedings. April 29-30, 1997, Kamloops, B.C. A. Vyse, C. Hollstedt and D. Huggard (editors), B.C. Min. For., Res. Br., Victoria, B.C. Working Paper 34. pp. 53-61	Seedling survival - Drought	The management of dry Douglas-fir forests of the Southern Interior is a subject of some concern to operational foresters and other land managers. Although the widespread use of uniform stand-level partial cutting rather than clearcutting in this forest type appears to have eliminated public fears about cutting practices, nagging doubts persist about the extensive use of this practice. The issues of regeneration, growth and yield, wildlife, pest management, and cattle grazing continue to be of concern despite the use of "continuous cover" silviculture. Formal research on some of these issues has been conducted for over 20 years in the Cariboo, Kamloops, and Nelson forest regions. Unfortunately, the results of this work are widely scattered in journals and other publications of varying accessibility. Other issues have received little attention. Added to this situation is the seemingly endless capacity of field foresters and loggers for invention. New approaches are always being discussed and applied in dry-belt Douglas-fir, as they are in other forest types in the province. Therefore, the foresters and others with responsibility for managing these forests are plagued by a double misfortune: they have difficulty learning from researchers and from the experiences of their peers. This workshop will not solve all of these problems. It was organized primarily to provide researchers with a forum to share research results, identify gaps, and set priorities for the future. However, the publication of the proceedings should also provide managers of dry Douglas-fir forests with a readily available source of information about the forest type and a starting point from which to make contact with the extensive knowledge base.

Foord, Vanessa & DeLong, Craig & Rogers, Bruce. (2017). A Stand-Level Drought Risk Assessment Tool for Considering Climate Change in Forest Management. 10.13140/RG.2.2.21992.72969.	Seedling survival - Drought	The stand-level drought risk assessment tool predicts tree mortality from moisture stress in a changing climate, based on the Biogeoclimatic Ecosystem Classification system in British Columbia. It can be used to include climate change impacts into forest management decisions. Increased drought, caused by recent regional warming, is believed to be one of the leading causes of tree mortality in forest ecosystems of western North America and worldwide. Changes in tree species distributions as a response to climate change have been examined at a broad level in British Columbia, but the varied response of individual tree species at the stand level to differing site properties, such as soil moisture regime, is needed to inform stand-level management. From 2009 to 2013, a Drought Risk Analysis and Decision Support Tool was developed by B.C. Ministry of Forests, Lands and Natural Resource Operations researchers. This Extension Note highlights the Stand-Level Drought Risk Assessment Tool methods, field validation, some of the current applications, and how the tool could be used in the future.
DeLong, S.C., H. Griesbauer, C.R. Nitschke, V. Foord, and B. Rogers. 2019. Development of a drought risk assessment tool for British Columbia forests using a stand-level water-balance approach. Prov. B.C., Victoria, B.C. Tech. Rep. 125. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tr125.htm	Seedling survival - Drought	We used an annual water-balance approach to assess the relative risk of cur-rent and future drought-induced stress and mortality at the stand level for tree species in British Columbia, Canada. The aim was to develop a drought risk–mapping tool that can be used by forest managers to inform harvest and silviculture decisions at the stand level. We used the concept of absolute soil moisture regime (ASMR), which equates to the ratio of actual evapotranspiration (AET) to potential evapotranspiration (PET), to compare estimates of ASMR class based on expert opinion with ASMR class calculated by a water-balance equation using long-term climate data and reference site and soil conditions for different site types. The quantitative estimates of ASMR class generally agreed with those based on expert opinion. Current tree distribution on ecologically classified units for which we could calculate AET/PET was used to determine the AET/PET limits for 10 common tree species in British Columbia. With climate warming we estimate that seven of the tree species examined may be at risk of drought-induced stress and/or mortality. Risk varied for these species across different climate and edaphic conditions. Under future climate, moist to wet site types were never projected to be in a moisture-deficit situation, suggesting that these sites are the most stable sites from a drought perspective under a changing climate and therefore should warrant extra consideration for forest conservation. We describe a variety of ways in which this research can be used to make forest management decisions.
Rehfeldt, Gerald. (1983) Genetic variability within Douglas-fir populations: Implications for tree improvement. Silvae Genetics, Volume 32: 9-14	Seedling survival - Drought an Frost	Genetic variances and covariances for growth potential, phenology and patterns of first year elongation were calculated from 30 half-sib families from each of three contrasting populations. Analyses of 4-year old trees growing in a single environment revealed high levels of additive genetic variance within populations. As a consequence, rather high estimates of genetic gains in growth potential were associated with weak selection intensities. However, genetic correlations were strong. Gains in growth potential were associated with delayed bud set and increased susceptibility to early fall frosts. For tree improvement to increase the growth potential of Douglas-fir without inadvertent degeneration of adaptation, selections must be based on several traits
Bansal, S., St. Claire, J., Harrington C. (2016) Tolerance to multiple climate stressors: a case study of Douglas-fir drought and cold hardiness. Ecology and Evolution 2016; 6(7): 2074–2083	Seedling survival - Drought and Frost	1. Drought and freeze events are two of the most common forms of climate extremes which result in tree damage or death, and the frequency and intensity of both stressors may increase with climate change. Few studies have examined natural covariation in stress tolerance traits to cope with multiple stressors among wild plant populations. 2. We assessed the capacity of coastal Douglas-fir (Pseudotsuga menziesii var. menziesii), an ecologically and economically important species in the north-western USA, to tolerate both drought and cold stress on 35 populations grown in common gardens. We used principal components analysis to com-bine drought and cold hardiness trait data into generalized stress hardiness traits to model geographic variation in hardiness as a function of climate across the Douglas-fir range. 3. Drought and cold hardiness converged among populations along winter temperature gradients and diverged along summer precipitation gradients. Populations originating in regions with cold winters had relatively high tolerance to both drought and cold stress, which is likely due to overlapping adaptations for coping with winter desiccation. Populations from regions with dry summers had increased drought hardiness but reduced cold hardi-ness, suggesting a trade-off in tolerance mechanisms. 4. Our findings highlight the necessity to look beyond bivariate trait – climate relationships and instead consider multiple traits and climate variables to effectively model and manage for the impacts of climate change on wide-spread species.
Darychuk, N. Hawkins,B.J.. and Stoehr, M. (2012) Trade-offs between growth and cold and drought hardiness in submaritime Douglas-fir. Can. J. For. Res. 42: 1530 – 1541 (2012)	Seedling survival - Drought and Frost	Trade-offs between growth and stress tolerance in plants may limit the possible phenotypes that can evolve or be selected. Such limits would have important implications for tree breeding. We examined evidence for trade-offs between growth and stress tolerance, particularly cold and drought tolerance, in 56 families of Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) from wild stand and seed orchard seed with a range of predicted growth rates. Families were assessed in field and controlled-environment experiments for growth and key physiological traits related to abiotic stress response. In the field, family growth was negatively correlated with fall and spring cold hardiness, indicating a trade-off between growth and cold hardiness. Combined results from field and controlled-environment experiments showed lower stomatal conductance and higher water potential in fast-growing families, indicating greater water conservation; thus no evidence existed for a growth – drought hardiness trade-off. Multivariate regression trees of normalized family means of growth and physiological parameters in the field split the families primarily by an index of continentality. Continental families had greater growth, survival, and fall hardiness than coastal families. We conclude that selection pressures in Douglas-fir have resulted in a trade-off between cold hardiness and high vigour, but little evidence exists for a trade-off between growth and drought hardiness.

Daintith, N., Newsome, T. (1996). Effect of mechanical site preparation and fencing on five-year growth Douglas-fir and lodgepole pine seedlings planted on dry sites in the Cariboo Forest Region. FRDA Report 252	Seedling survival - Drought and Frost	Douglas-fir plantations are difficult to establish in clearcut openings in the dry subzones of the Interior Douglas-fir (IDF) and Sub-boreal Spruce (SBS) biogeoclimatic zones in the Cariboo Forest Region. Seedlings planted in these openings are exposed to summer droughts and frosts, severe winter conditions, and potential physical damage by cattle. This study tested four mechanical site preparation treatments as methods for reducing environmental stresses and discouraging cattle use, thereby improving seedling survival and growth. It was conducted for both Douglas-fir and lodgepole pine seedlings, on grazed and ungrazed areas of IDFdk and SBSdw clearcuts. The study was established in spring 1988, on two sites Hances Timber (IDFdk4) and Sheridan Creek (SBSdw2). A smooth-wire exclosure was established on each site. Within the exclosure, and on adjacent ground outside the exclosure, four site preparation treatments were tested: V-plow, ripper plow, V-plow and ripper plow combination, and control (boot screef prior to planting). Two-year-old bareroot and one-year-old container lodgepole pine and Douglas-fir seedlings were planted on each site preparation treatment. Seedling microclimate was monitored for three growing seasons on the IDFdk4 site. Fifth- year seedling survival and condition and total height-growth (1988-1992) and diameter- growth (1989-1992) data are presented. On the Sheridan Creek site (SBSdw2), grazing and site preparation had little effect on seedling survival. Grazing also had little effect on seedling growth. Any of the site. preparation treatments tested would be suitable on similar sites, but the ripper plow and ripper/V-plow treatments resulted in significant increases in seedling growth compared to the control of boot screef and plant. Lodgepole pine is the best species for reforesting similar clearcuts in the SBSdw2 large container stock would be suitable. If Douglas-fir was prescribed, large stock (similar in size to the bareroot stock) would have the best potential to reach free-growing, provided the frost hazard of the site is low to moderate. On the Hances Timber site (IDF dk4), grazing generally had little effect on seedling survival with one exception. Survival of Douglas-fir container stock was reduced considerably with grazing, particularly on the control and V-plow treatments. Grazing also had little effect on seedling growth. Summer frosts are so severe on this site that none of the site preparation treatments tested alleviated the problem. While Douglas-fir survival was generally acceptable, seedling condition and growth were poor due to yearly frost damage. Therefore, lodgepole pine is recommended for regenerating similar IDFdk4 clearcuts, and ripper plow/V-plow site preparation is strongly recommended, especially if the site will be grazed.
Andrew J. Eckert, Andrew D. Bower, Jill L. Wegrzyn, Barnaly Pande, Kathleen D. Jermstad, Konstantin V. Krutovsky, J. Bradley St. Clair and David B. Neale (2009) Association Genetics of Coastal Douglas Fir (Pseudotsuga menziesii var. menziesii, Pinaceae). I. Cold-Hardiness Related Traits. Genetics 182: 1289–1302 (August 2009)	Seedling survival - Frost	Adaptation to cold is one of the greatest challenges to forest trees. This process is highly synchronized with environmental cues relating to photoperiod and temperature. Here, we use a candidate gene-based approach to search for genetic associations between 384 single-nucleotide polymorphism (SNP) markers from 117 candidate genes and 21 cold-hardiness related traits. A general linear model approach, including population structure estimates as covariates, was implemented for each marker–trait pair. We discovered 30 highly significant genetic associations [false discovery rate (FDR) Q < 0.10] across 12 candidate genes and 10 of the 21 traits. We also detected a set of 7 markers that had elevated levels of differentiation between sampling sites situated across the Cascade crest in northeastern Washington. Marker effects were small (r2 < 0.05) and within the range of those published previously for forest trees. The derived SNP allele, as measured by a comparison to a recently diverged sister species, typically affected the phenotype in a way consistent with cold hardiness. The majority of markers were characterized as having largely nonadditive modes of gene action, especially under dominance in the case of cold-tolerance related phenotypes. We place these results in the context of trade-offs between the abilities to grow longer and to avoid fall cold damage, as well as putative epigenetic effects. These associations provide insight into the genetic components of complex traits in coastal Douglas fir, as well as highlight the need for landscape genetic approaches to the detection of adaptive genetic diversity.