Article	Category	Abstract
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	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	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	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	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

Klenner, W., Walton, R., Arsenault, A., & Kremsater, L. (2008). Dry forests in the Southern Interior of British Columbia: Historic disturbances and implications for restoration and management. Forest Ecology and Management, 256(10), 1711–1722.	Climate	We critically examine the hypothesis that dry forests in southern British Columbia evolved in the context of a low-severity fire-dominated disturbance regime, that fire suppression has led to ecological conditions which are radically different from the past, and that “restoration” initiatives are required to re-establish former ecological conditions. Four sources of information were used to infer historic disturbance regimes and forest condition and to quantify the nature of disturbance since the early 1900s: (1) patterns of annual and seasonal weather and lightning strikes, (2) topographic variability, (3) records of wildfire, insect attack, and timber harvesting practices, and (4) early systematic forest surveys. Our analyses consistently indicate that historic natural disturbances were likely diverse and episodic at multiple spatial and temporal scales. High seasonal and annual variability in weather and the number of lightning strikes in complex topography suggest that a widespread low-severity fire regime is very unlikely, with a mixed-severity disturbance regime more consistent with our analyses. Although the nature of disturbance has changed from one largely dominated by fire and insect attack historically to harvesting and insect attack since 1950, the area disturbed annually has not diminished. Several interacting factors including climate, extensive fires coincident with European settlement, harvesting, fire suppression and insect attack have been key drivers in creating the conditions observed today. A complex, mixed-severity disturbance regime creates uncertainty about what represents “natural” forest conditions, or what the target conditions for restoration activities are if the objective is to “restore natural conditions”. We conclude that dry forest ecosystems in British Columbia typically experienced mixed-severity disturbance regimes that included fire, bark beetles and defoliators. Trying to “restore” these forests with applications of frequent, low-severity fire is not an ecologically sound objective over large areas. Landscape management should focus on maintaining forest heterogeneity that would have existed historically under a mixed-severity disturbance regime.
Rother, M., Veblen, T., & Furman, L. (2015). A field experiment informs expected patterns of conifer regeneration after disturbance under changing climate conditions. Canadian Journal of Forest Research, 45(11), 1607–1616	Climate	Climate change may inhibit tree regeneration following disturbances such as wildfire, altering post-disturbance vegetation trajectories. We implemented a field experiment to examine the effects of manipulations of temperature and water on ponderosa pine (Pinus ponderosa Douglas ex P. Lawson & C. Lawson) and Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) seedlings planted in a low-elevation, recently disturbed setting of the Colorado Front Range. We implemented four treatments: warmed only (Wm), watered only (Wt), warmed and watered (WmWt), and control (Co). We found that measures of growth and survival varied significantly by treatment type. Average growth and survival was highest in the Wt plots, followed by the Co, WmWt, and Wm plots, respectively. This general trend was observed for both conifer species, although average growth and survival was generally higher in ponderosa pine than in Douglas-fir. Our findings suggest that warming temperatures and associated drought are likely to inhibit post-disturbance regeneration of ponderosa pine and Douglas-fir in low-elevation forests of the Colorado Front Range and that future vegetation composition and structure may differ notably from historic patterns in some areas. Our findings are relevant to other forested ecosystems in which a warming climate may similarly inhibit regeneration by dominant tree species.
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	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.
Maxwell G. Wightman , Carlos A. Gonzalez-Benecke and Eric J. Dinger, 2019, Interactive Effects of Stock Type and Forest Vegetation Management Treatments on Douglas-Fir Seedling Growth and Survival—Ten-Year Results, Forests 2019,10,1002	Fdi Stock Types	In the Pacific Northwest, the use of forest vegetation management (FVM) and seedling stock type selection are important tools to ensure seedling establishment according to organizational objectives and state laws. Individually, these two reforestation decisions have been shown to increase growth and survival of Douglas-fir seedlings, however, the interaction between seedling stock type and level of vegetation control represents economic and ecologic tradeoffs that are less well understood. This study was designed to test the combined effects of three FVM regimes and three containerized stock types, one of which was experimental at the time, on Douglas-fir growth during the initial ten years of establishment on a site near Belfair, Washington (USA). When compared to the no-action control, FVM treatments reduced competitive plant cover below 20% during the year of application, and differences in vegetation cover persisted through the fifth growing season. Vegetation species diversity recovered quickly after FVM and there were no differences among the treatments by the third growing season. After ten growing seasons, trees in plots treated with FVM were 1.1 m taller with a mean diameter at breast height (DBH) 2.2 cm larger than those in the no-action control. Larger seedlings at the time of planting (styro-60) were 0.6 m taller with a mean DBH 1.1 cm larger than smaller seedlings (styro-8 and styro-15). The only significant stock type by FVM interaction in the experiment occurred with the survival of styro-60 seedlings growing in the no action control which had lower survival than all other treatment combinations (67% vs 91%). The long-term competitive impact of shrub cover was demonstrated by a strong non-linear relationship. Increasing cumulative shrub cover from 10% to 30% during the first two years of establishment reduced stand volume at year 10 by 79%.
Krasowski, M. (2003). Root system modifications by nursery culture reflect on post-planting growth and development of coniferous seedlings. The Forestry Chronicle, 79(5), 882–891	Nursery culture	A decade of the author's work evaluating effects of nursery culture on root system development in coniferous seedlings is reviewed. The studies include the evaluation of mechanical stability of young trees grown from different types of planting stock, root system deformations resulting from nursery culture, effects of mechanical and chemical pruning on root system development, hydraulic properties of the roots, and post-planting growth performance.
Romero, A., Ryder, J., Fisher, J., & Mexal, J. (1986). Root system modification of container stock for arid land plantings. Forest Ecology and Management, 16(1–4), 281–290.	Nursery culture	Root morphology is important for successful seedling establishment in semiarid lands. Production systems that improve root morphology, such as container volume, container configuration, and mycorrhizal inoculation influence root system development and ensure establishment success. Mycorrhizal inoculation has been enhanced by chemical root pruners that inhibit lateral root growth and promote short root development. These factors, when used in concert, ensure successful seedling establishment and rapid growth. Root/shoot ratios may be species-specific, and the optimal range may vary. Root/shoot ratios between 0.45-0.65 appear to produce seedlings that achieve balanced root and shoot growth, providing maximal potential for field survival.

Tinus, R. (1996). Root growth potential as an indicator of drought stress history. Tree Physiology, 16(9), 795–799.	Nursery culture	Container-grown quiescent Douglas-fir (Pseudotsuga menziesii var. glauca (Beissn.) Franco) seedlings were air dried to plant water potentials of –0.2, –2.2 or –3.8 MPa (unstressed, moderate, and severe stress treatments, respectively). Trees from each treatment were either placed in root mist chambers held at 10, 20, or 28 °C for 28 days and root growth potential (RGP) and plant water potential (PWP) measured weekly, or potted in a 1/1 mix of peat and vermiculite, watered only once, and height growth and survival recorded after 10 weeks in an unheated greenhouse. Root growth potential of unstressed trees was greater than that of moderately stressed trees at all temperatures. Root growth potential of severely stressed trees was zero. Predawn plant water potentials of unstressed and moderately stressed trees were initially high, fell to –0.5 to –0.8 MPa, and then increased. Predawn plant water potential of severely stressed trees declined continuously over the 28-day experiment. Survival and height growth of the severely stressed trees were reduced compared to the unstressed and moderately stressed trees. Among the root growth potential measurements, RGP measured after 7 days at 10 °C was most sensitive to drought stress history and revealed differences in vigor that were not apparent from the survival and height growth data.
van den Driessche, R. (1992). Changes in drought resistance and root growth capacity of container seedlings in response to nursery drought, nitrogen, and potassium treatments. Canadian Journal of Forest Research, 22, 740–749	Nursery culture	Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), lodgepole pine (Pinus contorta Dougl.), and white spruce (Picea glauca (Moench) Voss) seedlings, each represented by two seed lots, were grown in Styroblock containers in a greenhouse and plastic shelter house from February 1989 to January 1990. The seedlings were exposed to two nitrogen (N) treatments and three potassium (K) treatments arranged factorially within three drought treatments. After winter storage, seedlings from a complete set of treatments were planted into hygric, mesic, and xeric sand beds during 12–14 March. Increasing nursery drought stress increased survival of Douglas-fir and lodgepole pine after planting, and high N treatment level increased survival of lodgepole pine and white spruce. Under xeric conditions, combined nursery drought and high N treatments increased survival of lodgepole pine by 33%, indicating the importance of nursery cultural regime for stock quality. Increase in nursery drought decreased seedling size relatively little, but increase in N increased seedling size one season after planting. A positive relationship between shoot/root ratio and survival in lodgepole pine and white spruce indicated that increase in N increased both shoot growth and drought resistance over the N range investigated. Only Douglas-fir showed an interaction between drought and N treatment and a small response in both survival and dry weight to K. Root growth capacity, measured at the time of planting, showed an approximate doubling in all species due to high N treatment, and was also increased in white spruce by drought stress. Survival and root growth capacity were poorly correlated, but dry-weight growth in sand beds was well correlated with root growth capacity. Manipulation of root growth capacity by changing nursery treatment was possible without altering resistance to drought stress after planting.
Warwell, M., & Shaw, R. (2019). Phenotypic selection on ponderosa pine seed and seedling traits in the field under three experimentally manipulated drought treatments. Evolutionary Applications, 12(2), 159–174	Nursery culture	Drought-related selection during seedling emergence and early development may play a strong role in adaptation. Yet this process is poorly understood and particularly so in relation to ongoing climate change. To evaluate drought-induced differences in selection during early life stages, a total of 50 maternal families sampled from three climatically disparate ponderosa pine (Pinus ponderosa Doug.) populations were grown from seed in two common garden field experiments at a location that was warmer and drier than seed origins. Three drought treatments were imposed experimentally. Phenotypic selection was assessed by relating plant fitness measured as survival or unconditional expected height at age 3 to seed density (mass per unit volume), date of emergence, and timing of shoot elongation. In the year of emergence from seed, differential mortality was particularly strong and clearly indicated selection. In contrast, selection in subsequent years was far less pronounced. Phenotypes with high seed density, an intermediate but relatively early emergence date, and high 2nd-year early-season shoot elongation exhibited the greatest estimated fitness under drought. The form of selection varied among seed sources in relation to drought treatment. Selection was generally more acute in the cases of greatest difference between drought treatment and climatic patterns of precipitation at the site of seed origin. These results suggest that populations of ponderosa pine are differentially adapted to drought patterns associated with the climate of their origin. To the extent that the phenotypic traits examined are heritable or correlated with heritable traits, our results provide insight into how tree populations may evolve in response to drought.
Albrecher, S. (2012). Effects of planting quality, depth and medium on growth and survival of lodgepole pine (Pinus contorta) in south central British Columbia (University of British Columbia).	Operational Planting	Tree-planting quality, depth, and medium can significantly affect seedling growth, vigour, and survival in the Very Dry, Cool Montane spruce Biogeoclimatic subsone (MSxk). In this study, lodgepole pine (Pinus contorta) seedlings were planted in seven different treatment units to test for difference in growth and mortality. Trees were planted in F-layer, mineral soil, and poor medium, with damaged plugs, J-rooted, deep, and shallow treatments to test for these differences. All trees were measured two growing seasons after planting for nursery year growth (year 1 growth), second year growth, third year growth, caliper and mortality. Trees planted in the F-layer and mineral soil had significantly greater caliper than shallow planted seedlings which correlated strongly with third year growth, and survival. Third year seedling growth was significantly greater in F-layer, mineral screefs, and deep treatments. Mortality was greatest in shallow, poor medium and damaged root treatments and was likely caused by moisture deficit and drought. Total height differences were not found to be significantly different between treatments.

Illingworth, K. (1962). Planting Trials with Ponderosa Pine in the Nelson Forest District, 1960-1962 (Experimental Projects 552, 572 and 597): Final Report (No. 0552).	Operational Planting	In the period 1950 to 1952 inclusive, trials were established with the general objective of testing certain techniques which might improve the survival of planted ponderosa pine in the East Kootenays. Techniques included mechanical methods of eliminating vegetative competition, shading, residual effects of nursery treatments, planting stock age-classes and morphological grades and root-trimming. Conclusions after 3 years' observations are: I. The amount of precipitation during the growing season is apparently of primary importance to plantation survival. Thus, in wetter-than-average years, the effects of planting techniques, which are chiefly designed to improve plant-soil moisture relations, are not so pronounced as in dry years. However, any economically acceptable method of proven value should be incorporated into standard reforestation practice as an insurance against years of unfavourable weather. 2. Lateral shade (without screefing), provided by a shingle on the south-west side of each tree, was beneficial to survival, but no more so than manual screefing without shade. 3. While trees planted in furrows undoubtedly enjoy secondary benefits derived from the accumulation of moisture in the furrow bottoms, and from the reduction of evaporation by shading and sheltering of the soil surface, it appears that the greatest single factor contributing to improved survival is the removal of vegetative competition. Survival increased directly with the area so prepared. Thus, while there were no real differences in survival between mechanical methods of screefing (Skogskultivator) and furrowing, that obtained in relatively small (roughly 12 inches square), manually screefed patches was significantly poorer, and slit planting in unprepared ground was almost a complete failure. 4. By allowing furrows to weather, prior to planting, it was thought that fewer plants would be smothered by soil sloughing, and that the accumulation of snow-melt would materially aid establishment. In fact, survival in weathered furrows did not differ markedly from that in freshly prepared furrows. Thus, ploughing may be reserved for less busy periods of the year, permitting a more convenient distribution of the work load. It is noteworthy that, after three years, mortality among plants in weathered screefs (Skogskultivator) was significantly greater then in freshly prepared screefs. This is attributed to the difficulty of obtaining a clean screef in dry, sun-baked ground (autumn 1961). Many of the patches have been re-colonized by vegetation, whereas those prepared in the spring remain comparatively bare. 5. In terms of establishment costs per surviving plant, the Skogskultivator was generally most economical, although the importance of selecting a technique to suit the terrain was demonstrated. In particular, the plough and Skogskultivator in combination with light tractors were inoperable on uncleared sites with much antelope brush or many windfalls and stumps, nor was the plough suitable for stony sites. In these cases, furrowing with a tilted or angled bulldozer blade was preferable in every respect. 6. In the 1961 trial, the survival of the 2 + 1 and 1 + 2 age-classes was distinctly better than that of 2 + 0 and 1 + 1. In the 1962 trial, however, there was no real difference in survival between the 1 + 2 and 2 + 0 classes. 2 + 1 stock was again distinctly superior to all others, and 3 + 0 seedlings were the poorest. The relatively poor survival of the 1 + 2 stock in 1962 is tentatively attributed to the poorly balanced type of plant comprising the 1 + 2 class in that year. Both the 1 + 2 and 3 + 0 classes were characterized by heavy tops (approximately 18 cm) and low root-top ratios. Thus, while the survival of 2 + 1 transplants was consistently highest in the years and on the sites encompassed by the trials, the annual variability in the quality of the planting stock classes necessitates caution in drawing generalizations about the performance of age-classes. 7. In terms of total cost per surviving plant, 2 + 0 seedlings were slightly cheaper (by 1.0 to 1.4 cent per tree) than 2 + 1 transplants. 8. Within particular classes of stock, the survival of large grades (based upon top length and stem diameter at the ground line) was very significantly better than that of small grades, and, although the difference was only of the order of 10 percent, it is such as to justify the nursery grading of plants, within a class, on the basis of calliper and top length. 9. Field survival was strongly influenced by the type of soil amendment with which the nursery seedbeds had been treated, and it would appear that this influence does not necessarily work indirectly through its effect upon planting-stock size. 10. Trimming the roots to 8 or 12 inches (below the root collar) at the planting site, to facilitate planting, had no detectable influence upon survival during the
Campbell, D., Jones, M., Kiiskila, S., & Bulmer, C. (2003). Two-year field performance of lodgepole pine seedlings: Effects of container type, mycorrhizal fungal inoculants, and site preparation. B.C. Journal of Ecosystems and Management, 3(2), 1–11.	Operational Silviculture	Seedlings were planted into different rooting environments in two separate locations, encompassing two separate experiments. In experiment 1, seedlings were planted into fully rehabilitated landings (ripped with burn-pile debris and topsoil incorporated), ripped landings, and unprepared cutblocks in the spring. In experiment 2, seedlings were planted in a cutblock in manually screefed (i.e., boot screefed) planting sites or undisturbed forest floor planting sites in the summer. Seedlings in the fully rehabilitated landings were 21% taller, had 45% larger diameters, and were more vigorous than seedlings in landings that were simply ripped; seedlings planted in the unprepared cutblock were taller, but with a smaller diameter, than those on the rehabilitated landings. Seedlings in screefed microsites grew significantly larger (5%) than seedlings planted directly in the forest floor. After 2 years in the field, the sizes of spring-planted, noninoculated seedlings, and seedlings inoculated with ectomycorrhizal fungi were not significantly different. Inoculated summer-planted seedlings were approximately 5% larger than non-inoculated control seedlings. Among the variables we manipulated, planting environment had the greatest influence on seedling growth.
Dennis Farquharson, 2011, USDA Forest Service Procedings RMRS P 65 2011	Operational Silviculture	The challenge for a silviculturist is the creation of a seedling microsite that is favorable enough for the seedling to not only survive, but thrive. The silviculturist must do this without irrigation, heat, glass, plastic, or daily monitoring and manage-ment. The silviculturist does this by understanding the needs of the forest seedlings and the shortcomings of the reforestation site and by using management techniques to bring them closer together. There are, in fact, only four main things that young seedlings need: nutrition (food), water, soil, and sunlight. A good sup-ply of these, in keeping with seedling needs, will ensure that the roots of the young seedling will grow well. If the roots grow well, the top will also grow well, as the top is largely a product of the roots. When the above-ground portion of our young seedling is healthy and growing well, it is able to better overcome the injuries and challenges it encounters. With our management activities that lead up to outplanting seedlings, we are working to create a balance of soil air, wa-ter, and nutrition so seedling roots will grow quickly. At the same time, our management activities are designed to protect seedlings by minimizing or eliminating challenges we expect them to encounter, such as vegetation competition, root rots, snow creep, cattle damage, and occasional animal feeding (voles, rabbits, and deer).

Harrington, Timothy B, David H. Petera, Robert A. Slesak (2018) Logging debris and herbicide treatments improve growing conditions for planted Douglas-fir on a droughty forest site invaded by Scotch broom. Forest Ecology and Management (2018) 31-39	Operational Silviculture	Logging debris has the potential to benefit forest regeneration by increasing resource availability, modifying microclimate, and altering plant community structure. To understand potential mechanisms driving these benefits, we initiated research at a forested site on the Olympic Peninsula, WA that contained the invasive, nonnative competitor, Scotch broom (Cytisus scoparius). Immediately after harvesting the stand of mature coast Douglas-fir (Pseudotsuga menziesii var. menziesii) in late 2011, two levels of logging debris retention were created on replicated plots: 18.9 and 9.0 Mg ha −1 , with debris depths averaging 32 and 17 cm, respectively. Within each plot, three herbicide treatments (aminopyralid (A), triclopyr ester (T), and A + T) and a non-sprayed control were applied to split plots in August 2012. Douglas-fir seedlings were planted in early 2013, and microclimate and seedling performance were monitored through 2016. During the growing seasons of 2012–2014, soil water content was greater and soil temperature was lower under heavy debris than under light debris. Survival of planted Douglas-fir seedlings declined an average of 45 and 11 percentage points after intense summer droughts in 2015 and 2016, respectively, but it averaged 7–10 percentage points greater in heavy debris than in light debris during this period. Douglas-fir stem diameter growth was consistently greater in heavy debris than in light debris, with the exception of treatment A + T where diameter did not differ between debris treatments. A re- ciprocal regression model (R 2 = 0.55) predicted that total stem volume of Douglas-fir increased from 19 to 84 dm 3 ha −1 as Scotch broom cover decreased from 20% to 0% as a result of the logging debris and herbicide treatments. There were limited treatment effects on mineral soil chemical and physical properties, but forest floor mass and nutrient content were increased in the heavy debris treatment. Five years after forest harvesting (2016), logging debris mass in heavy debris differed little from that in light debris at study initiation, indicating a substantial reduction in fuels and the potential for severe wildfire. Results suggest that, on gravelly soils and possibly other droughty forest ecosystems in the Pacific Northwest, heavy debris will benefit planted Douglas-fir by improving growing conditions and by limiting abundance of nonnative competitors, such as Scotch broom.
Helgerson, O. (1985). Survival and Growth of Planted Douglas-Fir (Pseudotsuga menziesii (Mirb.) Franco) and Ponderosa Pine (Pinus ponderosa Dougl . ex Laws.) on a Hot, Dry Site in Southwest Oregon. Tree Planters' Notes, 36(4), 3–6.	Operational Silviculture	After two growing seasons on a hot, dry site at low elevation in southwest Oregon, survival rates were 88% for 1 +0 plug Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), 99% for 2+0 bareroot Douglas-fir, 91% for 1 +0 plug ponderosa pine (Pinus ponderosa Dougl. ex Laws.), and 98% for 2+0 bareroot ponderosa pine. Survival of the bareroots was significantly greater than that of the plugs (P = 0.05). Stress testing ranked all four stock types as excellent. Relative volume growth was greatest for the pine. The initially smaller 1 +0 plug pine nearly equaled the size of the 2+0 bareroot Douglas-fir after 2 years.
Jacobs, D., & Timmer, V. (2005). Fertilizer-induced changes in rhizosphere electrical conductivity: Relation to forest tree seedling root system growth and function. New Forests, 30(2–3), 147–166	Operational Silviculture	Fertilization is standard practice in forest tree seedling nursery culture. Additionally, fertilization at outplanting has potential to facilitate nutrient uptake and reduce transplant shock. Fertilization, however, may dramatically alter rhizosphere chemical properties such as pH, ion availability, and electrical conductivity (EC). These changes may inhibit root system growth and function by reducing soil osmotic potential and creating specific ion toxicities. The risk of root damage associated with high EC levels appears to be dependent on species, age of root system, and soil moisture availability. Root inhibition in container nursery culture of conifers is likely to occur above 2.5 dS m(-1), though threshold EC levels for bareroot culture and field plantings are largely unavailable. Fertilization at outplanting has the added risk that drought conditions may prevent leaching of excess fertilizer salts, which can increase rhizosphere EC beyond safe levels and ultimately impair root uptake of water or nutrients. For fertilization programs to be successful, a critical threshold balance must be maintained between optimizing seedling nutrient availability in the rhizosphere, while minimizing potential for root damage. Future research is needed to identify optimal EC levels for a range of species across all stages of the reforestation process, from nursery culture through plantation establishment.
Pinto, J., Marshall, J., Dumroese, K., Davis, A., & Cobos, D. (2012). Photosynthetic response, carbon isotopic composition, survival, and growth of three stock types under water stress enhanced by vegetative competition. Canadian Journal of Forest Research, 42(2), 333–344.	Operational Silviculture	Selecting the proper stock type for reforestation on dry sites can be critical for the long-term survival and growth of seedlings. In this study, we use a novel approach to understand stock type selection on a site where drought was induced with vegetative competition. Three ponderosa pine (Pinus ponderosa Lawson & C. Lawson var. ponderosa C. Lawson) seedling stock types were planted in the field and subjected to three levels of competition. Winter wheat (Triticum aestivum L. em.) was sown in three densities (0, 150, and 300 plants•m–2) and was successfully used as a model competitor to create drought conditions. High rates of net photosynthesis (A) indicated that seedlings with adequate soil moisture and without vegetative competition were established within three weeks. Conversely, low A, low soil moisture, and low predawn water potential measurements indicated that seedlings planted with vegetative competition were moisture-stressed and not established. Drought conditions created by the wheat caused 100% mortality among smaller stock types, whereas the largest stock type had a 63%–75% mortality rate. Measures of stable carbon isotopes showed stratification based on water availability, with significant δ13C enrichment in competition treatments. Soil moisture is critical for seedlings to establish quickly after planting. Our data suggest that proper stock type selection on drought- or vegetation-prone sites can confer survival and growth benefits.
Randall, W., & Johnson, G. (1998). The impact of environment and nursery on survival and early growth of Douglas-fir, Noble fir, and white pine--A case study. Western Journal of Applied Forestry, 13(4), 137–143.	Operational Silviculture	Survival and third-year height were examined on 2,383 reforestation units from 1983 to 1994 to determine which factors impact reforestation success. Survival of Douglas-fir (Pseudotsuga menziesii) varied by as much as 20% from year to year. The most significant factor affecting reforestation success was the nursery that provided the seedlings. Nursery impacted both survival and height of Douglas-fir and impacted height for noble fir (Abies procera) and white pine (Pinus monticola). No nursery was best for all species. Other factors that were important for all three species were the administrative unit where the seedlings were planted, initial plant height, aspect, and length of storage prior to planting. Other significant factors that were important for Douglas-fir were seed origin, planting month, protection, stock type, and aspect. For noble fir, other important factors were planting month and stock type; for white pine, the other important factor was slope. Elevation of the seed source and the planting unit affected Douglas-fir survival and height but did not affect the other two species. This supports the smaller elevational bands for Douglas-fir compared with noble fir and white pine.
Stechyshyn, John (2019). Gabriel Courchesne-Normandin. Compendium on the Challenges of Douglas Fir Regeneration in the Interior Douglas Fir BEC dk3/dk4 Subzones and Strategies to Improve Reforestation.	Operational Silviculture	Reforestation in the Interior Douglas Fir (IDF) Biogeoclimatic zone is an important and contemporary subject matter in BC. In 100 Mile house alone "the forest sector accounts for 26% of total basic employment – the second-highest sector" (100 Mile House Timber Supply Area, 2012). The recent Mountain Pine Beetle epidemic has put strain on the timber supply for the interior of the province. The shrinking timber supply was further reduced after the unprecedented wildfires of 2017. An estimated 1.2 million hectares were burned. Areas in the IDF were particularly affected by the fires and the short to medium term supply is a significant threat to the communities that depend on the forest industry. The following pages represent a condensed synthesis of the findings from academic and applied studies and recommendations on how to successfully reforest the IDF.
Stone, E. (1955). Coniferous seedling survival: Poor survival may be due to physiological conditions associated with root-producing ability of planting stock. California Agriculture, 9(2), 7–15	Operational Silviculture	At least half of the more than 12 million coniferous seedlings planted in California during the past five years failed to survive their first summer in the field. Part of this failure can be related to factors such as rodents, livestock, and competing vegetation. On the other hand, there are many instances where the reason is not apparent; not even the long summer drought nor the high temperatures associated with California's Mediterranean-like climate are satisfactory explanations.

Bingham, M., & Simard, S. (2013). Seedling genetics and life history outweigh mycorrhizal network potential to improve conifer regeneration under drought. Forest Ecology and Management, 287, 132–139.	Seedling genetics	The objective of this study was to determine whether interior Douglas-fir (Pseudotsuga menziesii var. glauca) seedling establishment is affected by the presence of an ectomycorrhizal network (MN), and whether this varies by regional climate, seed provenance and seedling life history. We examined how MN facilitation varied with seedling provenance by planting interior Douglas-fir seed and nursery-grown seedlings near the crown edge of mature conspecific trees along a climatic stress gradient. Survival of outplanted nursery seedlings was greatest for the medium moisture provenance, but decreased with drought more rapidly than the wet or dry provenances. The driest provenance performed best under severe drought, but the survival of all provenances was still less than 35% under severe drought. Survival, growth and δ 13 C of seedlings grown from seed or in the nursery were not affected by MNs. We conclude that seedling genetic and life history effects outweigh benefits that MNs may incur upon Douglas-fir seedling performance under conditions of severe drought. Selection of appropriate provenances and robust growing stock will become of increasing importance for regenerating sites where drought is expected to increase with climate change.
Pickles, B., Twieg, B., O'Neill, G., Mohn, W., & Simard, S. (2015). Local adaptation in migrated interior Douglas-fir seedlings is mediated by ectomycorrhizas and other soil factors. New Phytologist, 207(3), 858–871	Seedling growth	Separating edaphic impacts on tree distributions from those of climate and geography is notoriously difficult. Aboveground and belowground factors play important roles, and determining their relative contribution to tree success will greatly assist in refining predictive models and forestry strategies in a changing climate. In a common glasshouse, seedlings of interior Douglas-fir (Pseudotsuga menziesii var. glauca) from multiple populations were grown in multiple forest soils. Fungicide was applied to half of the seedlings to separate soil fungal and nonfungal impacts on seedling performance. Soils of varying geographic and climatic distance from seed origin were compared, using a transfer function approach. Seedling height and biomass were optimized following seed transfer into drier soils, whereas survival was optimized when elevation transfer was minimised. Fungicide application reduced ectomycorrhizal root colonization by c. 50%, with treated seedlings exhibiting greater survival but reduced biomass. Local adaptation of Douglas-fir populations to soils was mediated by soil fungi to some extent in 56% of soil origin by response variable combinations. Mediation by edaphic factors in general occurred in 81% of combinations. Soil biota, hitherto unaccounted for in climate models, interacts with biogeography to influence plant ranges in a changing climate.
Augustine, S., & Reinhardt, K. (2019). Differences in morphological and physiological plasticity in two species of 1st-year conifer seedlings exposed to drought result in distinct survivorship patterns. Tree Physiology.	Seedling growth	First-year tree seedlings represent a critical demographic life stage, functioning as a bottleneck to forest regeneration. Knowledge of how mortality is related to whole-seedling carbon and water relations is deficient and is required to understand how forest compositions will be altered in future climatic conditions. We performed a greenhouse drought experiment using first-year seedlings of two common pine species found in the Intermountain West, USA. Gas exchange, biomass gain, allometry and xylem water potentials were compared between well-watered and droughted seedlings from emergence until drought-induced mortality. In both species, morphological adjustments to confer drought tolerance, such as increased leaf mass per unit area, were not observed in seedlings exposed to drought, and droughted seedlings maintained photosynthesis and whole-seedling carbon gain well into the experiment. Yet, there were important differences between species in terms of carbon budgets, physiological responses and mortality patterns. In Pinus ponderosa P. & C. Lawson, physiological acclimation to drought was much greater, evident through stronger stomatal regulation and increased water-use efficiency. Photosynthesis and carbon budgets in P. ponderosa were greater than in Pinus contorta Dougl. ex. Loud., and survival was 100% until critical hydraulic thresholds in leaf water content and seedling water potentials were crossed. In P. contorta, physiological adjustments to drought were less, and mortality occurred much sooner and well before injurious hydraulic thresholds were approached. First-year conifer seedlings appear canalized for a suite of functional traits that prioritize short-term carbon gain over long-term drought tolerance, suggesting that conifer seedling survival is linked with carbon limitations, even during drought, with survival in species having narrower carbon survival margins being more hampered by carbon limitations.
Burdett, A. (1990). Physiological processes in plantation establishment and the development of specifications for forest planting stock. Canadian Journal of Forest Research, 20(4), 415–427	Seedling growth	Both the morphological and physiological characteristics of forest planting stock vary widely with nursery culture and environment. Through the control of environmentally determined variation in phenotype, stock can be adapted to both the stress of transplanting from nursery to forest site and the particular environmental conditions of the forest site. Evidence is discussed that indicates that the stress of transplanting is primarily water stress, resulting from (i) the confinement of roots to the planting hole, (ii) poor root–soil contact, and (iii) low root permeability. These deficiencies are overcome by root growth, which is thus a central process in plantation establishment. Root growth depends largely on current photosynthesis. Photosynthesis depends on the assimilation of carbon dioxide at the expense of lost water in transpiration. Transpiration is limited by water uptake and hence depends on root growth. Root growth and photosynthesis in newly planted trees are thus mutually dependent. Because of this relationship, plant water status immediately after planting, or as soon as conditions favorable to root growth occur, is a crucial factor in determining plantation establishment success. High plant tissue water status immediately after planting, or as soon as environmental conditions permit root growth, allows the onset of a positive cycle of root growth supported by photosynthesis and photosynthesis supported by root growth; whereas low tissue water potential immediately after planting can lead to the inhibition or root growth by a lack of photosynthesis and the inhibition of photosynthesis by a lack of root growth. Stock characteristics that enhance plant water status immediately after planting are reviewed and the scope for their control considered. Stock characteristics affecting adaptation to particular planting site conditions, or capable of affecting postestablishment plantation performance, are also discussed.
Grossnickle CS (2018) Seedling establishment on a forest restoration site – An ecophysiological perspective. Reforesta 6: 110-139.	Seedling growth	Seedling field performance is affected by both their quality and restoration site conditions. Seedlings enter the establishment phase when they start to develop root systems into the surrounding soil and are coupled to the restoration site. Once seedlings are established, their inherent growth potential is related to morphological and physiological attributes and their ecophysiological response to site environmental conditions, which ultimately determines field performance. This establishment phase is a time when seedlings developed with certain nursery cultural practices begin to respond to site conditions. This phase is also a period when silvicultural practices have created microsites intended to benefit established seedlings field performance. Seedlings can be exposed to a wide range of environmental conditions during the establishment phase, some of which may be extreme enough to exceed their ability to physiologically tolerate environmental stress. When this occurs, seedling growth on the restoration site is reduced. On the other hand, this phase can provide planted seedlings with ideal environmental conditions that allow for an optimum physiological response and maximization of their growth potential. An understanding of the ecophysiological capability of planted seedlings can ensure their best chance at rapid stand establishment.

Grossnickle SC (2016) Restoration Silviculture: An Ecophysiological Perspective - Lessons learned across 40 years. Reforesta 1: 1-36.	Seedling growth	Involvement in forest restoration programs across North America for the past 40 years, dealing with nursery cultural practices, operational seedling quality programs and defining seedling performance on restoration sites has given me a unique perspective, which I have used to examine programs from both a research and operational perspective. Certain biological patterns and themes continually appeared across these programs and this paper discusses five of the most common themes. Learning To Think Like a Tree – It is important for practitioners to develop an understanding of the ecophysiological performance of tree species in a nursery or forest restoration program in order to understand how seedlings grow. This understanding leads to sound biologically based cultural decisions to improve seedling performance. Stress and the Cyclical Nature of Stress Resistance – Seedlings are exposed to stress when environmental conditions limit their performance. Plants develop physiological resistance attributes to mitigate stress and these attributes change throughout the seasonal cycle. Practitioners have developed hardening cultural practices that enhance seedling stress resistance, thereby improving seedling quality and site restoration success. Seedling Quality: Product versus Process – Seedling quality is an important component of successful restoration. Typically seedling quality is examined from a product perspective, thus defining functional integrity, operational grading or sometimes performance potential. An alternative approach monitors the process, with product quality the final output. Planting Stress and Seedling Establishment – Planting stress is prevalent in forest restoration. The act of planting can result in a seedling that does not have proper connections for water movement through the soil-plant-atmosphere continuum (SPAC). Seedling water stress, reduced growth performance and potentially death can occur if this SPAC connection is not restored. Seedling Death: Sometimes Simple and Sometimes Complicated – Seedling death can occur in restoration programs as a result of environmental extremes or incorrect management practices. Some problems can be easy to diagnose and correct practices can be implemented to rectify the problem. Other times, issues are complicated and it can be a challenge to define the potential factors causing seedling death.
Lopushinsky, W., & Beebe, T. (1976). Relationship of shoot-root ratio to survival and growth of outplanted Douglas-fir and Ponderosa pine seedlings (No. PNW-274).	Seedling growth	Two-year-old Douglas-fir and ponderosa pine seedlings with three top heights, and with either large or small roots, were planted in a burned-over area in north-central Washington to evaluate the relationship of shoot-root ratio to first-year survival and shoot growth. Survival of fir seedlings with large roots was 22 to 26 percent higher than survival of seedlings with small roots, and pine survival was increased 5 to 15 percent. Shoot growth (increase in shoot mass) of large-rooted fir and pine seedlings was as much as 2.1 and 4.8 times, respectively, that of small-rooted seedlings. Height growth of both fir and pine seedlings with large roots was 1.2 to 1.7 times that of seedlings with small roots.
Lopushinsky, W., & Kaufmann, M. (1984). Effects of Cold Soil on Water Relations and Spring Growth of Douglas-fir Seedlings. Forest Science, 30(3), 628–634.	Seedling growth	Effects of low soil temperature on the water relations, shoot growth, and root growth of Douglas-fir seedlings (Pseudotsuga menziesii (Mirb.) Franco) were studied to evaluate the significance of reduced water uptake and growth in seedlings outplanted in cold soils. Transpiration rate declined linearly with decreasing soil temperature, and at 1.3°C, was 18.8 percent of the rate at 20.2°C. Xylem pressure potential of seedlings maintained under high evaporative demand for 10 days in soil at 1.3°C averaged -20.0 bars, compared to a higher potential (-13.4 bars) for seedlings in soil at 26°C. Stomatal conductance of seedlings in cold soil was 50 percent or less of seedlings in warm soil. Low soil temperature reduced shoot growth and completely prevented root growth. The results indicate that for seedlings planted in cold soil, reduced water uptake does not immediately cause lethal water stress. The primary cause of poor field survival probably is suppressed root growth at low soil temperature resulting in increased susceptibility to summer drought.
Parke, J., Linderman, R., & Black, C. (1983). The role of ectomycorrhizas in drought tolerance of Douglas-fir seedlings. New Phytologist, 95(1), 83–95.	Seedling growth	Experiments were conducted to test the relative ability of mycorrhizal and non-mycorrhizal Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] seedlings to tolerate and recover from drought conditions, using reduction in CO_2 fixation as an overall indicator of plant moisture stress. Seedlings were watered daily or conditioned to cyclic drying and re-wetting of the soil. Net photosynthetic rates of mycorrhizal and non-mycorrhizal seedlings watered daily did not differ significantly; however, drought-stressed mycorrhizal seedlings fixed CO_2 at a rate ten times that of non-mycorrhizal seedlings. Total leaf water potentials of mycorrhizal plants were lower (more negative) than those of non-mycorrhizal plants but they recovered more rapidly. Non-mycorrhizal seedlings and seedlings inoculated with four ectomycorrhizal fungus species were allowed to become desiccated, then were rewatered and compared for their ability to tolerate and recover from drought. Seedlings inoculated with Rhizapogon vintcolor were less affected by drought than any of the other mycorrhizal or non-mycorrhizal treatments. Net photosynthetic rate of Rhizopogon-inoculated seedlings 24 h following re-watering was seven times that of non-mycorrhizal seedlings. The transpiration rate of Rhizopogon-inoculated seedlings was low before desiccation, declined rapidly during the drought period and, after re-watering, quickly resumed a rate higher than that for other treatments.
Steven C. Grossnickle 2005. Importance of root growth in overcoming planting stress. New Forests. 2005 30:273-294	Seedling growth	Root growth is critical to the establishment of planted seedlings. Seedlings can undergo stress just after planting if root growth is not sufficient to couple the seedling to available soil water. Stress occurs when a newly planted seedling's root system can not supply enough water to tran-spiring needles to maintain a proper water balance and ensure survival. Thus, a newly planted seedling's ability to overcome planting stress is affected by its root system size and distribution, root–soil contact, and root hydraulic conductivity. This paper describes how factors of root growth and water status of newly planted seedlings are important in overcoming the phenomenon of planting stress which then allows a newly planted seedling to enter the establishment phase of development.
Steven C. Grossnickle 2012. Why seedlings survive. New Forests. May 2012	Seedling growth	This review examines the value of commonly measured seedling quality attributes (i.e., height, diameter, root mass, shoot-to-root ratio, drought resistance, freezing tolerance, nutrient status, root growth potential, and root electrolyte leakage) that have been ecognized as important in explaining why seedlings with improved attributes have better growth after planting.

Steven C. Grossnickle Joanne E. Macdonald. 2017. Seedling Quality: History, Application and Plant Attributes. Forests. 2018, 9, 283	Seedling growth	Since the early 20th century, silviculturists have recognized the importance of planting seedlings with desirable attributes, and that these attributes are associated with successful seedling survival and growth after outplanting. Over the ensuing century, concepts on what is meant by a quality seedling have evolved to the point that these assessments now provide value to both the nursery practitioner growing seedlings and the forester planting seedlings. Various seedling quality assessment procedures that measure numerous morphological and physiological plant attributes have been designed and applied. This paper examines the historical development of the discipline of seedling quality, as well as where it is today. It also examines how seedling quality is employed in forest restoration programs and the attributes that are measured to define quality. The intent is to provide readers with an overall perspective on the field of seedling quality and the people who developed this discipline from an idea into an operational reality.
Steven C. Grossnickle Joanne E. Macdonald. 2017. Why seedlings grow: influence of plant attributes. New Forests. August 2017	Seedling growth	This paper discusses the need to plant high quality seedlings to increase chances for successful establishment and growth. It also indicates that forest practitioners need to specify the characteristics of seedlings that will meet their needs. It indicates that drought tolerance can be cultured at the nursery but would only last until shoot development starts. "Greater root system size and stem diamter, which enhances water uptake and transport to foliage, respectively confer a higher chance of avoiding planting stress and enhancing seedling growth." "A smaller shoot system or lower S:R are critical attributes where dry soils and high evaporative demands are limiting factors"
Warren, J., Brooks, J., Meinzer, F., & Eberhart, J. (2008). Hydraulic redistribution of water from Pinus ponderosa trees to seedlings: evidence for an ectomycorrhizal pathway. New Phytologist, 178(2), 382–394	Seedling growth	While there is strong evidence for hydraulic redistribution (HR) of soil water by trees, it is not known if common mycorrhizal networks (CMN) can facilitate HR from mature trees to seedlings under field conditions. Ponderosa pine (Pinus ponderosa) seedlings were planted into root-excluding 61-μm mesh barrier chambers buried in an old-growth pine forest. After 2 yr, several mature trees were cut and water enriched in D2O and acid fuchsin dye was applied to the stumps. Fine roots and mycorrhizal root tips of source trees became heavily dyed, indicating reverse sap flow in root xylem transported water from stems throughout root systems to the root hyphal mantle that interfaces with CMN. Within 3 d, D2O was found in mesh-chamber seedling foliage > 1 m from source trees; after 3 wk, eight of 10 mesh-chamber seedling stem samples were significantly enriched above background levels. Average mesh-chamber enrichment was 1.8× greater than that for two seedlings for which the connections to CMN were broken by trenching before D2O application. Even small amounts of water provided to mycorrhizas by HR may maintain hyphal viability and facilitate nutrient uptake under drying conditions, which may provide an advantage to seedlings hydraulically linked by CMN to large trees.
Baker, W. (2018). Transitioning western U.S. dry forests to limited committed warming with bet-hedging and natural disturbances. Ecosphere, 9(6), e02288 (1-29).	Stand dynamics	Historical evidence suggests natural disturbances could allow more forest persistence, than expected from models, over 40 yr of transition to the net-zero emissions needed to limit warming to <2.0°C. Forests must ultimately equilibrate with committed warming from accumulated emissions. Historical dry-forest landscapes were heterogeneous from large, infrequent disturbances (LIDs) that reduced tree density and basal area, followed by slow, variable tree regeneration and recovery for 1–3 centuries. These together effectively provided bet-hedging through stand- and landscape-level heterogeneity that enhanced resistance and resilience to a diversity of unpredictable subsequent disturbances. Recent disturbances have not yet exceeded historical variability in rates and patterns, but could cause mortality of ~26–51% of dry-forest area in the transition. This also means 1/2 to 3/4 of dry-forest area could escape most mortality and the mortality area could also have substantial forest persistence. Projections are unavailable for droughts or beetle outbreaks, but they recently caused about 3–4 times as much tree mortality as did moderate- to high-severity fires. Mortality could reduce forest area if new trees do not regenerate, but 24 studies showed recent regeneration after high-severity fires was slow, but indistinct from historical variability. Survival of smaller trees provided regeneration after beetle outbreaks and droughts. Regeneration in general was projected by 2060 to decline by ~10% in one study and increase by 50% in another. If openings from disturbances increased, some grasslands and shrublands could be restored, increasing landscape heterogeneity and resistance to disturbance spread. Given these trends and our limited ability to prevent LIDs, I suggest (1) refocusing restoration to increase bet-hedging resilience to droughts and beetle outbreaks by retaining small trees and diverse tree species, (2) expanding development of fire-safe landscapes to protect people and infrastructure from unavoidable increased fire, (3) enabling more managed fire to restore and enhance stand- and landscape-scale bet-hedging, and (4) accepting that LIDs will revise resistance, resilience, and adaptation, which enhance forest persistence, particularly if post-disturbance survivors are not logged and trees are not planted. Natural disturbance and slow recovery, if bet-hedged to increase resistance and resilience, could enable substantial forest persistence.
Bingham, M., & Simard, S. (2011). Do mycorrhizal network benefits to survival and growth of interior Douglas-fir seedlings increase with soil moisture stress? Ecology and Evolution, 1(3), 306–316	Stand structure	Facilitation of tree establishment by ectomycorrhizal (EM) networks (MNs) may become increasingly important as drought stress increases with climate change in some forested regions of North America. The objective of this study was to determine (1) whether temperature, CO2 concentration ([CO2]), soil moisture, and MNs interact to affect plant establishment success, such that MNs facilitate establishment when plants are the most water stressed, and (2) whether transfer of C and water between plants through MNs plays a role in this. We established interior Douglas-fir (Pseudotsuga menziesii var. glauca) seedlings in root boxes with and without the potential to form MNs with nearby conspecific seedlings that had consistent access to water via their taproots. We varied temperature, [CO2], and soil moisture in growth chambers. Douglas-fir seedling survival increased when the potential existed to form an MN. Growth increased with MN potential under the driest soil conditions, but decreased with temperature at 800 ppm [CO2]. Transfer of 13C to receiver seedlings was unaffected by potential to form an MN with donor seedlings, but deuterated water (D2O) transfer increased with MN potential under ambient [CO2]. Chlorophyll fluorescence was reduced when seedlings had the potential to form an MN under high [CO2] and cool temperatures. We conclude that Douglas-fir seedling establishment in laboratory conditions is facilitated by MN potential where Douglas-fir seedlings have consistent access to water. Moreover, this facilitation appears to increase as water stress potential increases and water transfer via networks may play a role in this. These results suggest that conservation of MN potential may be important to forest regeneration where drought stress increases with climate change.