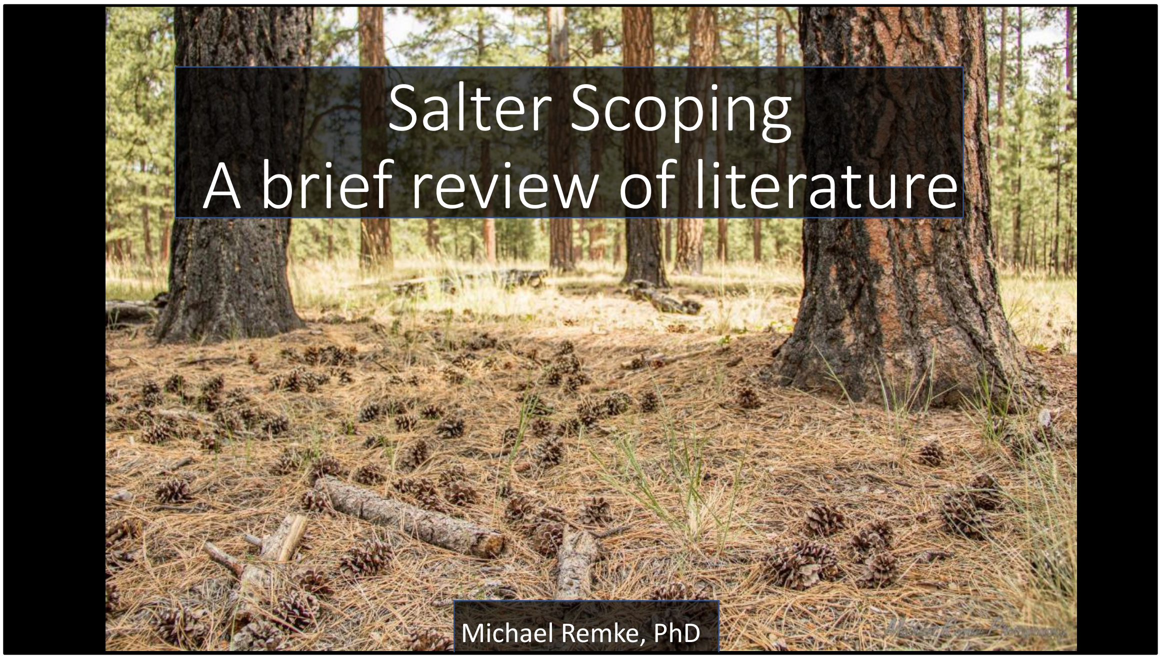


This presentation and information is designed to skim the surface of the most relevant literature to southwestern Colorado ponderosa pine forests. In some cases I use literature from other tree species because they exemplify the content well and studies of similar nature are limited or non-existent in SW Colorado or in ponderosa pine in general. Such knowledge gaps highlight interesting research opportunity. Additionally, some topics are covered briefly, and the papers represent the most directly relevant in a brief literature review. A more thorough review on any topic could be completed with more time.

Outline

- Diameter caps in ponderosa pine
  - How are diameter caps used to achieve project goals/objectives in silviculture
  - What are ecological implications of diameter caps?
- Roundheaded pine beetle outbreak
  - How does roundheaded beetle interact with host trees/populations?
- What are potential ecological impacts of climate change within the Salter Geography?
- How can silvicultural treatments enhance adaptive capacity of ponderosa pine forests?

Implications of Diameter Caps

- Abella et al. 2006 – Literature Review and field study
  - Identify key viewpoints
    - In favor of
    - Neutral
    - Against

Abella et al. recognize that those in favor of diameter caps often advocate for diameter caps because of lack of trust within agency decision making processes and fear that economics and industry would drive decisions. Those against diameter caps often argue that economics and the need to pull viable commercial grade timber are important.

Diameter Caps

- Greatest impact of diameter caps on stands containing many >16 inch post-settlement trees (Abella et al. 2006)

Abella et al. show that where there are few trees less than 16” in diameter, diameter caps had no viable effect on prescriptions because they were irrelevant, however, when there was an abundance of trees over 16” diameter caps significantly altered the prescription.

Diameter Caps - Ecology

- Openings and Meadows
  - Understory Vegetation
  - Wildlife Habitat
- Where abundant large trees exists – diameter caps inhibited making openings
- Diameter caps may make new meadows rather than recreate old ones

Abella et al. 2006 and Triepke et al. 2011 before show diameter caps can limit the creation of openings and meadows where >16” diameter trees are abundant. Both these papers are based on 16” diameter caps because of how common these have become in southwest Ponderosa pine forests. If fast growing post-settlement trees exists, they often become large young trees that occur in historical openings (away from historical stumps). A diameter cap can limit the removal of these post-settlement trees and therefore prevent opening up the canopy to release understory vegetation, create and maintain meadows for wildlife habitat. Abella et al. (2006) also highlight that this could result in the creation of meadows where meadows were not historically present and this phenomena may result in novel plant communities because of plant-soil interactions.

Diameter Caps – Pine Autecology

- Genetics
  - Thinning post-settlement tress >16" DBH = increased genetic diversity
  - If regeneration limited, diameter caps increase seed source diversity but may decrease microsites favorable for regeneration
  - Genetic diversity is needed for resilience (Gehring et al. 2017)

Pinon Pine example: Gehring et al. 2017

Drought tolerant Phenotype

Insect tolerant Phenotype

Abella et al. (2006) also highlight that if numerous fast-growing post settlement trees exist on the landscape that removal of some of these trees can help allow prescriptions to leave some smaller trees on the landscape and thus maintain increased genetic diversity while obtaining the same basal area targets. Alternatively, in regeneration limited systems diameter caps may enhance seed source diversity though diameter caps may also decrease microsites favorable for regeneration. Careful monitoring in regard to regeneration, and microsites needed for regeneration (canopy cover, litter, bare soil, etc) can help address these concerns.

Gehring et al. (2017) provide an excellent example of why genotype diversity is relevant with Pinon pine. The drought tolerant phenotype is susceptible to insects while the insect tolerant phenotype being susceptible to drought. In this case, the phenotype posses easily observable difference with one possessing a shrub-like growth form and the other possessing a tree like growth form. Gehring in follow up studies has demonstrated the importance of maintain seed sources of both trees to preserve genetic diversity on the landscape. These lessons can be considered for ponderosa pine, however, phenotypes may be less obvious (more later).

Diameter Caps – Pine Autecology

- Timber Production
  - Diameter caps decrease short term timber production
  - May increase long term timber production
    - Especially if result is more even spaced fast growing trees

Abella also considers timber yields created by diameter caps and suggests that diameter caps may limit the short term timber production markets by preventing the removal of larger trees, however, in the long term, release created from initial entry may increase timber production in the long term. If long-term contracts are considered, diameter caps may want to be re-considered for second entry if initial treatment results in abundance of large diameter trees.

Diameter Caps – Gambel Oak

- Diameter caps can constrain thinning post-settlement trees
  - Slows down oak growth
- Opening of canopy can result in extensive oak release
  - (Van Auken et al. 2017; Korb et al. unpublished)

Abella et al. 2006 suggests that diameter caps can leave higher canopy cover than not having diameter caps and canopy cover can constrain growth of Gambel oak. This was conducted in Northern Arizona where Gambel oak tends to take on a more tree-like growth form. In southwest Colorado, however, we tend to have more extensive shrub like cover of oak and opening the canopy tends to result in oak release (Van Auken et al. 2007 and Korb et al. in progress). Van Auken (2017) demonstrate that in New Mexico oak behaves like an early successional species and as oak matures it eventually starts restricting its own growth to begin taking on a more grouped tree form. Shrub cover could limit tree regeneration and careful monitoring can address these phenomena. Maintenance of openings for lower shrub cover could be maintained by repeated entry or disturbance via prescribed fire (Harrington et al. 1989).

Diameter Caps -- Soils

- Nutrients
  - Openings yield high Nitrogen mineralization rates
- Microorganisms
  - Openings also haver higher soil respiration rates
- Diameter caps can inhibit meadow creation when post-settlement trees >16" are abundant
- Abella et al. 2006

Abella et al. (2006) summarize some literature that demonstrate higher nitrogen mineralization rates and soil respiration rates in meadows. These studies were primarily in grass dominated meadows where mycorrhizal fungi are abundant and are likely contributing to these phenomena. Given that diameter caps can inhibit meadow creation, diameter caps may slow down landscape scale ecosystem processes by limiting mineralization rates and soil organic material turnover.

Diameter Caps – Water Relations

- In Beaver Creek, Arizona
  - 75% removal of basal area
    - 22% increase of stream flow
  - Diameter cap may decrease streamflow due to canopy interception
  - Abella et al. 2006

Abella et al. 2006 pulled data from the Bever Creek experimental Watershed which demonstrated a 75% reduction of basal area resulted in 22% increase in stream flow of a sub watershed. It is important to note that in this watershed, Ponderosa pine forests are the dominate forest type and . It should be noted that Simonin et al. 2007 demonstrate water balance and evaporative loss in thinned and un-thinned stands varied during extreme droughts and suggest that particularly wet periods will result in less difference between thinned and un-thinned. Results from these studies should be interpolated to other geographies with caution. In SW Colorado, water consumption from oak in forest thinning operations could actually yield net decrease in water yield. Additionally, the ponderosa pine landscape makes up a small amount of the total area that contributes to water ielf in much of SW Colorado. A more thorough review of the literature should be conducted before assuming this patters would be mimicked on our landscape.

Diameter Caps - Fire

- Again, dependent on current conditions
- Greater fire risk reduction without diameter cap when many post-settlement trees >16" DBH are present
- Abella et al. 2006

If openings and or canopy connectivity cannot be broken up because of diameter caps when there is abundance of trees >16” than diameter caps can reduce effectiveness of thinning on preventing risk for fire. That being said Baker (2018) suggest that mixed severity fire occurred on the landscape in Ponderosa pine forest and is not uncharacteristic. More on fire later

Diameter Caps – What size?

- Based on 4FRI prescriptions
  - (Sanchez-Meador et al. 2015)
- Smaller diameter caps resulted in conditions more similar to untreated

Sanchez-Meador et al. 2015 modeled impacts of diameter caps of different sizes and looked at the implications of their outputs in comparison to untreated scenarios. These efforts were conducted on the 4FRI landscape. They revealed smaller diameter caps more closely resulted in conditions more similar to untreated.

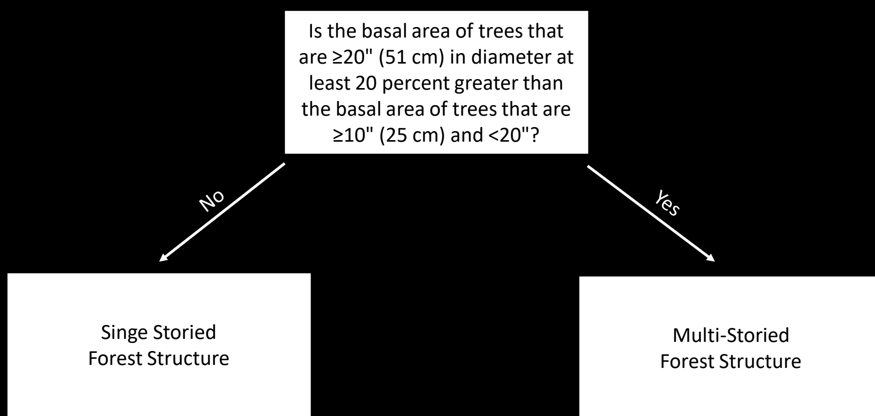
Diameter Caps – What size?

- Based on 4FRI prescriptions
  - (Sanchez-Meador et al. 2015)
- 16, 20, and 24 inch caps
  - No difference in basal area, canopy cover, diameter distribution

Sanchez-Meador et al. 2015 built these models for the 4FRI prescriptions and demonstrated that there were no differences in basal area, canopy cover, or diameter distribution based on 16, 20, or 24 inch diameter caps. These findings support that the size of diameter classes may not significantly alter outcomes, however, determining whether or a not a diameter cap should be used and then what size of diameter cap is used could be determined based on current conditions? *Note, I put a question mark here because there is no empirically driven method to determine what size of diameter cap should be used, however, knowing diameter distributions can still be a useful tool.

Perhaps the most common theme revealed through all these of these studies is that treatments should depend on both current conditions and specific objectives.

Diameter Caps – Decision Trees



(Triepke et al. 2011)

Diameter caps

- Where desired conditions were met with diameter caps
  - Few large trees existed
    - Diameter cap not necessary
- Where large trees existed
  - Desired conditions were not met with diameter cap

(Triepke et al. 2011)

Diameter Caps – Summary

- Depends on project objectives AND site conditions
- This information is relevant on the stand level
  - Abella et al. 2006 and Sanchez-Meador et al. 2015

Abella et al. 2006 and Sanchez-Meador both convey that this information carries the most significance at the stand-level for implementation of prescriptions and treatments. They both suggest that conditional planning based on current conditions can help leave flexibility in decisions across landscape scale implementation.

Old-trees vs large trees

- Fast growing young trees versus old-trees (Brown et al. 2019).
  - Identifying old tree characteristics

Brown et al. (2019) helped create traits of old trees to help distinguish old trees from fast growing trees. He shows that for ponderosa pine, flattened crowns and deep furrows on the bark can help identify old trees. Using traits to distinguish old trees can help achieve desired conditions while maintaining old trees on the landscape.

Round headed beetle

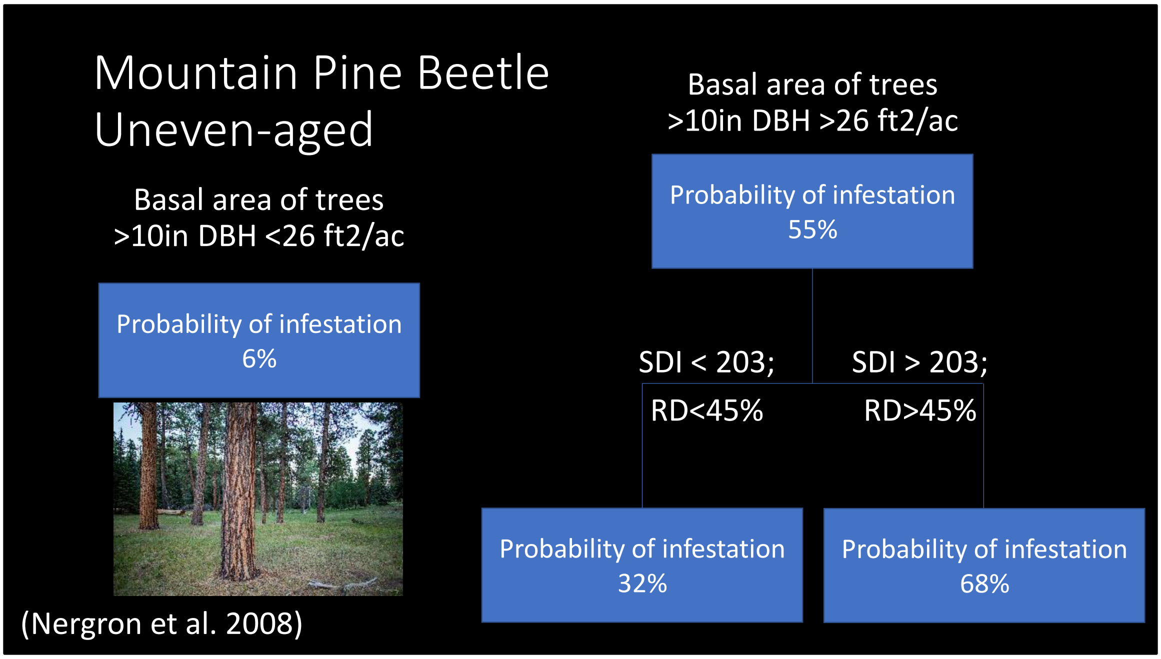
- Attack and colonize susceptible trees in October/November
- Outbreaks generally rare…
- 1950 and 1990s outbreaks

Negron et al. 2000 documented outbreaks in Utah, New Mexico, and Arizona. Outbreaks generally occurred following drought. Round headed were also observed on the Kaibab plateau following a fire, but in very few trees. They are common in low numbers and with low impact to stands or tree health/vigor.

Round headed Beetle

- Infested stands
  - Increased basal area
  - Greater trees per hectare
  - Reduced growth rate
  - Lower diameter (likely co-correlated with higher density of small trees)
    - (Negron et al. 2000)

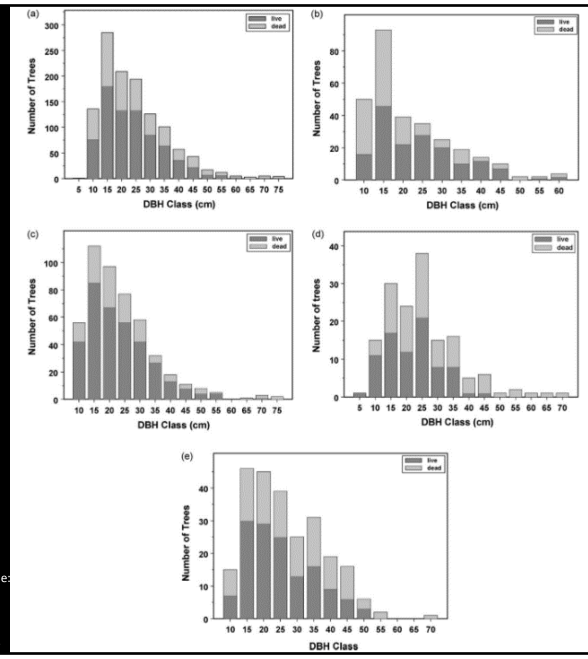
Negron et al. measured stands infested with round headed beetles and compared them to uninfected stands in similar area. Stand conditions for each geography were different, however, stands associated with infection generally had increased basal area, more trees per hectare, reduced growth rate, and lower median diameters. Lower median diameters maybe correlated with higher densities of smaller trees.



Given the low sample size and occurrence of round headed beetle outbreaks, comparing stand characteristics of stands infected with round headed beetle are comparable to infestations of mountain pine beetle in un-even aged ponderosa pine forests. The above flow chart can be useful for determining probability of infestation. Basal area of trees over 10 inches and then the stand density index or relative density are the most useful pieces of information for determining if probability of infestation is high.

Round headed Beetle

- Mortality occurs in numerous stands
  - But only 25% of measured plots
- Small scale variation in space and time
- Utah and Arizona
- (Negron et al. 2009)
- Sometimes larger trees attacked
- (Negron et al. 2009, Jeske thesis, 2018)



Number of live and bark beetle-killed ponderosa pines, Pinus ponderosa, across diameter classes in the: (a) all forests combined [chi-square = 57.3, $p < 0.0001$]; (b) Apache Sitgreaves National Forest [chi-square = 64.6, $p < 0.001$]; (c) Coconino National Forest [chi-square = 15.8, $p = 0.3$]; (d) Tonto National Forest [chi-square = 33.1, $p < 0.002$]; and (e) Prescott National Forest [chi-square = 15.4, $p = 0.2$]; Chi-square compares the distribution of live and dead trees across diameter classes, Arizona, 2003– 2004.

Mortality only occurs in 25% of Negron et al. (2009)s measurable plots, otherwise pitch tubes were often observed along with confirmation of round headed beetle, however mortality never happened. This indicates that even within sites, there was a large amount of variation in space and time. Across sites, there was more variation in the number of trees killed by beetles, often varying by diameter class. On the Tonto and Coconino, more mortality was occurred in larger trees, but all sizes of trees, mortality occurred. Jeske's undergraduate thesis also demonstrated larger trees are sometimes more commonly attacked.

Round headed Beetle

Basal area > 105 ft2/ac

Probability of infestation
72%

5 year Periodic Annual
Growth Increment
<0.26 in

Probability of infestation
95%

(Nergron et al. 2000)

Two factors observed by Nergron et al. 2000 that show heightened probability of infestation were stand BA >105 ft2/acre (elevated densities) and 5 year periodic annual growth increments that are less than 0.26 inches per year. The later of these scenarios is likely the result of tree growth that was slowed by drought or other stressors.

Round headed Beetle

- Larger trees with thick phloem
- Slow growing in last ten years, stressed trees

(Fischer et al. 2010).

Fischer et al. documented individual tree traits that correspond to round headed beetle attack. Fischer found larger trees with thick phloem and slow growing trees in the last ten years were both more susceptible to round headed beetle induced mortality. It is possible that stressed trees are the reason for tree growth to slow.

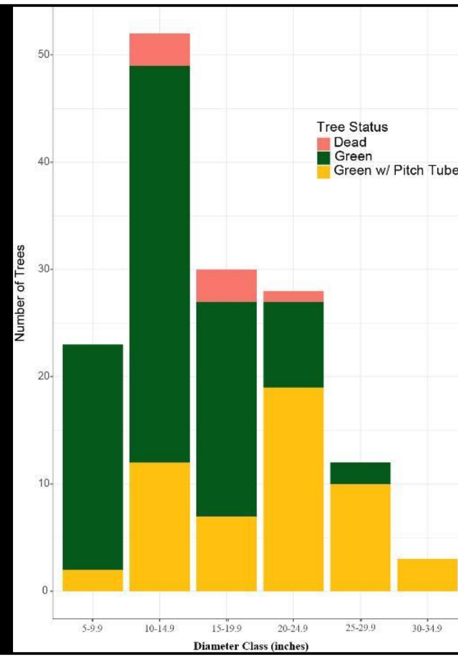
Round headed Beetle

- Following fire – All Dendroctonus species
  - Trees with 30-70% crown mortality most susceptible
  - Trees with >70% crown mortality died by fire, not beetle
  - (McHugh et al. 2003)

McHugh et al. 2003 showed crown mortality following fire made trees more susceptible to attack from any Dendroctonus species, round headed beetle was only present in one of their sites on the Kaibab Plateau. Trees with 30-70% crown mortality from fire were more likely to be attacked by beetles. Trees with more than 70% crown mortality often died by fire and were untacked by beetles.

Round headed Beetle

- Plateau fire geography
  - Data collected in 2019
  - No mortality observed
    - 148 trees measured

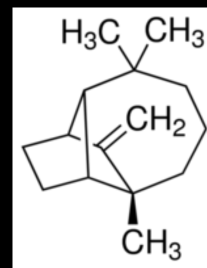


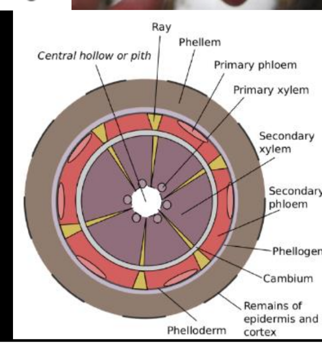
On the Plateau fire geography, Mountain Studies institute documented tree status with regard to beetle presence in 1/10th acre plots. We recorded trees as green (with no beetle evidence), green trees with pitch tubes, brown trees with pitch tubes, dead trees with pitch tubes and dead trees with no pitch tubes. In our plots, all dead trees had 100% crown loss from the Plateau fire and thus mortality was likely the result of fire and not beetle activity.

Round headed Beetle

- Tree traits associated with attack….
  - Slow diameter growth
    - **Most decrease of growth during recent drought**
  - Thicker phloem
  - Lower percentages of longifolene
    - Longifolene is a chemical attractant to male beetles
    - Produced in trees, released in sap during beetle attack

(Negron et al. 2000, Fischer et al. 2010).





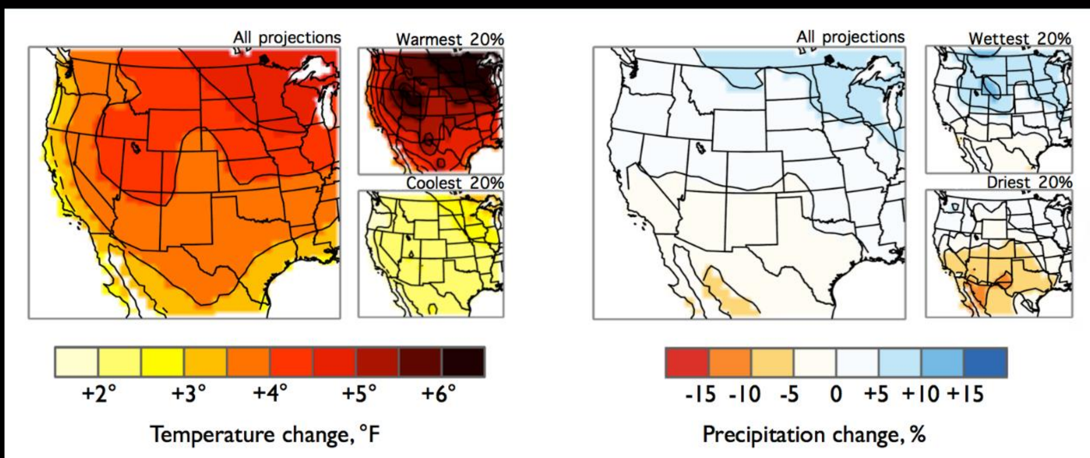
Fischer et al 2010 identified numerous individual tree traits associated with trees attacked by round headed beetles. These traits are trees with slow diamter growth, specifically in the last 5-10 years; trees with thicker phloem; and trees with lower percentages of longifolene. These traits are all traits that are genetic and heritable. All of these traits can be measured directly, though measurements are time consuming including tree ring analysis, biochemical assays. In direct measurements of these traits can also be made.

Round headed Beetle -- Implications

- **Genetic diversity** favors trees that are resistant to beetle (Fischer et al. 2010)
- Survivors genetically distinct, traits heritable (Six et al. 2018).
- Fast growing trees and trees resilient to other stressors also benefit stands that are resistant to beetle (Negron et al. 2000 and 2009).

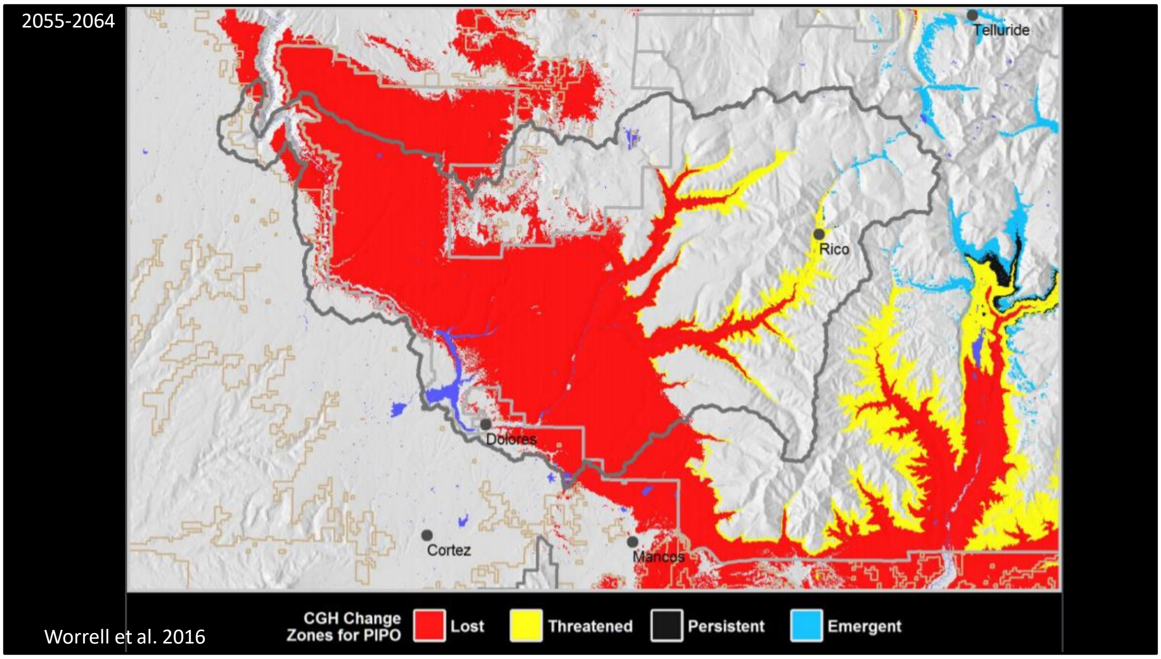
Genetic diveristy can favor trees that are resilient to diverse disturbances, including drought and beetle mortality (Negron et al. 2000 and 2009; Fischer et al. 2010). Additionally, trees that survive outbreaks may be trees that possess traits that are resistant to beetle attack, however, knowing which trees will survive prior to an attack can be difficult (Six et al. 2018). These traits could be selected for in nursery settings, however, capturing tradeoffs to other disturbance events will also be important (Gehring et al. 2017).

Climate Change -- Models



Lukas et al. 2014 under RCP 4.5

Lukas et al. 2014 and numerous climate specialists have modeled projected climate change impact under various relative concentration pathways which are based on various carbon dioxide emissions. RCP 2.6, 4.5, 6 and 8.5 are the RCP pathways, the values represent atmospheric radiative forcing (W/m2) given carbon dioxide emissions where RCP 2.6 assumes halting carbon dioxide emissions immediately, and 8.5 assumes steady human population growth to 9 billion people and increases of carbon dioxide per-capta in line with current rates. We have already surpassed the carbon dioxide emissions assumed in RCP 2.6 have already been surpassed. The above maps for RCP 4.5 suggest strong warming trends of 3-5 degrees F for SW Colorado by 2060. Precipitation is variable with anywhere from drier to wetter occurring. Regardless warming temperatures mean increased evapotranspiration and thus a drier world. The reality is more volatile precipitation regimes are likely with more inter-and intra-year variation in precipitation.



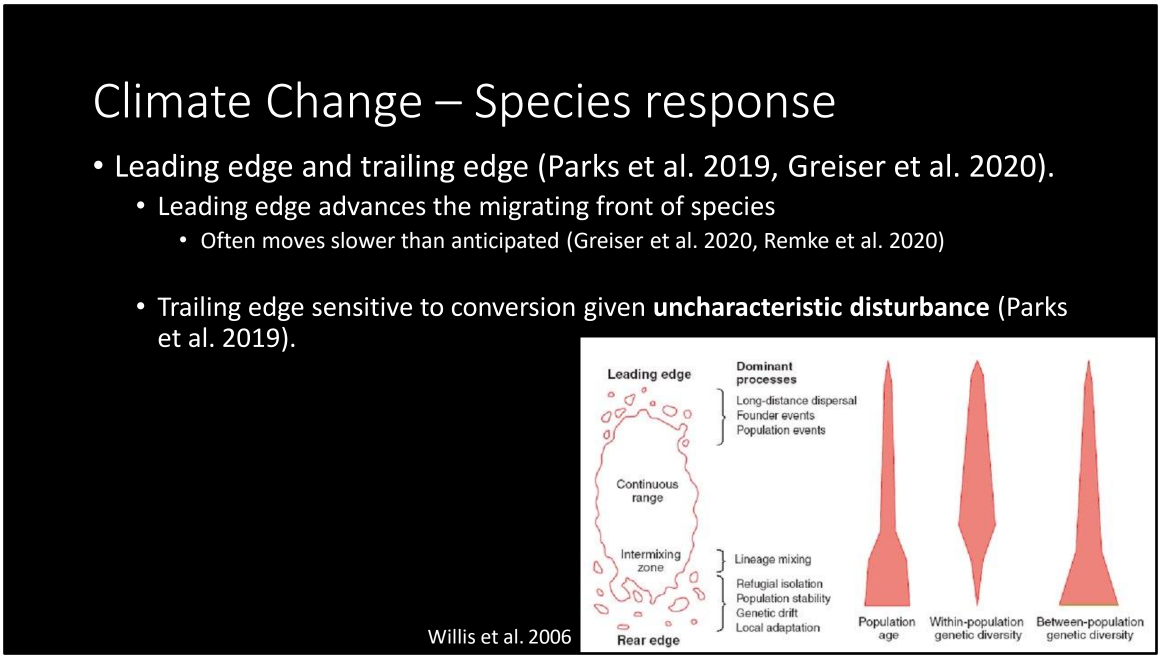
Worrell et al. 2016 used Random Forest and Forest Service Inventory analysis data to model current and projected Ponderoa pine bio-climatic distribution given an averaged prediction across RCP 4.5, 6, and 8. Random Forest is a Machine Learning based decision tree that uses numerous input variables (precipitation, climate, elevation) etc to determine which variables best predict presence of a species. The algorithm tends to complete 1000s of iterations of the model and then selects the models that perform best. Mathemetics as to how variables are selected and computationally predict presence remain a "black box", however, mathematics supporting metrics of model fit are provided. These approaches are useful when dealing with complex or numerous inputs and thus can be considered prediction tools. FIA data was used to train the model and validate presence data, and then new climate values were used to project predicted species presence given climate change. Worrell et al. Then used some mathmetical generalizations of comparing predicted future distribution to current distribution to determine species lost, threatened, persistent, or emergent.

These models assume climate variables to be the primary determinants of presence thus assume for lost to occur, extent living trees must also die.

Critiques of Worrell

- 2055-2064
- Averaged RCP 4.5, 6.0, and 8.5 values to obtain projected climate scenario
- Bioclimatic factors only – ignores processes, biotic factors etc.
- Black box approach – Random Forest
- Other models look different….

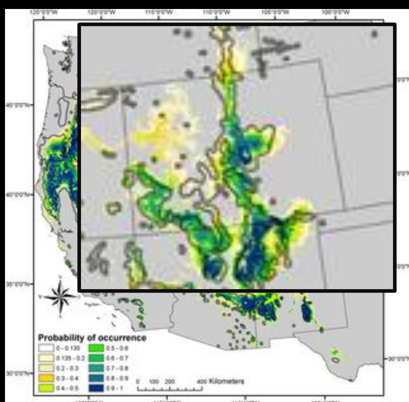
“All models are wrong, but some are useful” -George Box



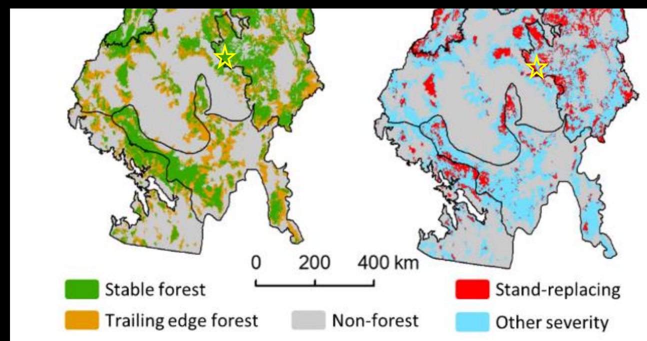
The reality of species change is more complicated than assuming all populations of a species will respond in the same way. Leading edges of species distributions (the migrating front) are often genetically distinct from the continuous range or rear (or tailing) edge of a species distribution. Willis et al. Highlight some of these distinctions. Whitam et al. And numerious other researchers have more closely studied some of these phenomena.

Parks et al. 2019 modeled forests to determine where trailing edge populations may be and compared these populations to high severity fire probabilities to determine which forests may be sensitive to conversion.

Climate Change – Species response



Shinneman et al. 2016



Parks et al. 2019

Shinneman et al. Sow probability of occurrence for 2060 to be closer to >0.5 with some areas having lower probability. Pakrs et al. 2019 suggest most of the San Juans are stable forest however, some areas may be at risk for stand replacing wildfire. Many studies including Rodman et al. 2019 show limited ponderosa pine regeneration following wildfire in the San Juans with Climate Water Deficit being a key predictor for whether ponderosa pine or other species are able to regenerate.

Climate Change – Dry forests

- Increased density can increase drought stress (Clark et al. 2016, Bottero et al. 2017).
- Increased drought → increased threat to insect outbreak (Baker & Williams 2015)
- Fast growing trees tend to exhibit drought stress faster than slow growing trees (Roskilly et al. 2019)

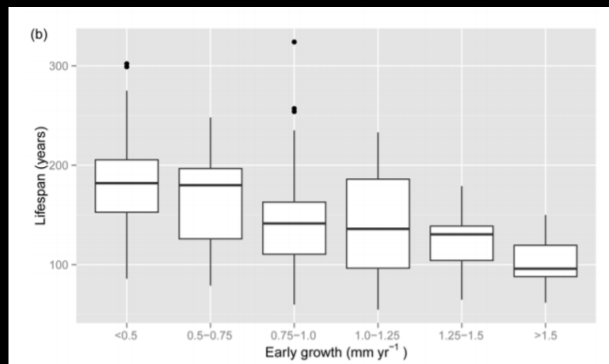


Fig 2. Distribution of tree size and lifespan versus early growth. Boxplots of (a) DBH_{ib} (diameter at breast height inside bark) at the time of tree death; and (b) lifespan. The variables are plotted for different classes of early growth (mean ring width over the first 50 years; n = 160 trees).

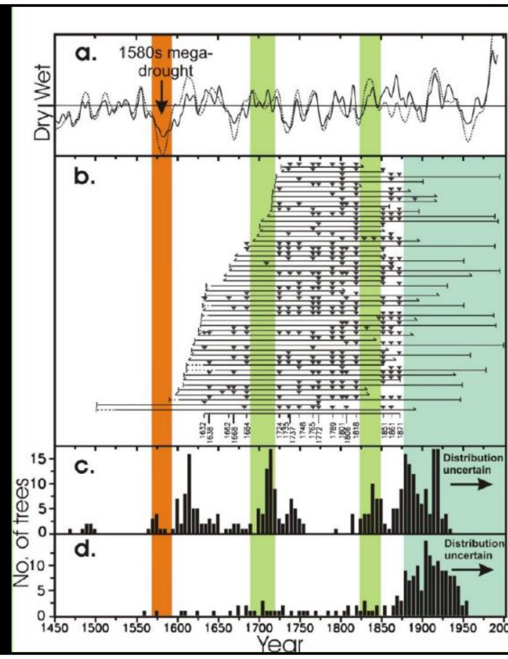
Bigler 2016, *Pinus montana*

Increased tree density can increase drought stress (Clark et al 2016; Bottero et al. 2017) and increased drought stress can make dry forests more prone to insect outbreaks (Baker & Williams 2015). Some traits in trees can predispose trees to drought stress, like being fast growing trees with thicker phloem and thicker xylems (Roskilly et al. 2019), these trees typically have shorter life spans and exhibit stress given water becoming a limting factor (Bigler et al. 2016). Bigler's study was on Pinus montana, however, Roskilly's results in part validate Bigler's data in Pinus ponderosa.

MR1

Climate Change -- Regeneration

- Ponderosa regeneration correlated with climate
  - Wet, fire free periods = episodic regeneration on Archuleta Mesa
    - (Brown & Wu 2005)
- Phenotypic variation in seedlings can facilitate stress tolerance, even at trailing edge
  - Specifically root allocation
    - (Kolb et al. 2016)
- In tact plant – soil relationships, including soil biota results in seedlings that perform better during drought
  - Disrupting mutualisms through soil disturbance may minimize seedling survival
    - (Remke et al. 2020)



Brown & Wu on Archuleta Mesa outside of Pagosa Springs documented periods of tree regeneration in ponderosa pine are often correlated with periods that are wetter than normal. These periods result in brief fire free periods that all trees to grow and survive past the initial seedling phase. Kolb et al. 2016 demonstrated that different phenotypes (genetic x environment) of ponderosa pine can survive drought better, even in the lower elevation trailing edge populations. Specifically, he demonstrated phenotypes that had a genetic predisposition towards root allocation tended to better survive drought. Lastly, Remke et al 2020 demonstrated that ponderosa pine seedlings growing in conditions 4 degrees F warmer than their population source have are more likely to survive if native soil is intact and not disturbed. This is likely due to increased water use efficiency from symbionts contributing to hydraulic redistribution of water.

Climate Change – Fire

- Extended fire season potential from earlier snowmelt
  - Climate and fire interactions could dramatize shifts in vegetation (Huerteau et al. 2013, Stephens et al. 2020).
- Longer fire season and more variability in precipitation could create more variability in area burned year-year and within year
  - (Liu et al. 2013)

Climate change is likely to have some impacts on fire season. Longer fire season potential from earlier snowmelt could cause longer fire seasons that result in dramatic shifts in fire season (Liu et al. 2013, Huerteau et al. 2013, Stephens et al. 2020).

Climate Change – Fire

- Fuel limited systems may see decrease in fire because of lack of fuel
  - (Littell et al. 2018).
- Lower montane likely to see increased fire risk (short-term) but decreased risk in the long term (lack of regeneration, new fuel)
  - (Rocca et al. 2014)

It is important to note that climate change could also limit new fuel accumulation (Littell et al. 2018), and thus limit future fire activity. Rocca et al. 2014 suggests that the lower montane is likely to see increased fire risk in the short-term, but the post fire environment combined with climate change is likely to result in limited regeneration and growth of fuels, thus long-term fire risk will likely decrease.

Climate Change -- Implications

- Thinning of overly dense stands can promote growth rates and resilience to drought
  - (Kolb et al. 2006, Stephens et al. 2020)
- Genetic diversity yields greatest resilience to….
  - Drought (Kolb et al. 2016)
  - Beetles (Fischer et al. 2010)
- Preventing un-characteristic disturbance is the best option for maintaining species
  - (Parks et al. 2019)

Numerous studies have indicated that reduced basal are promotes drought resilience of trees of all sizes and can improve growth rated and artificial thinning can help achieve these conditions (Kolb et al. 2006, Stephens et al. 2020). Additionally, genetic diversity yields resilience to multiple potential disturbances including drought and beetles (Kolb et al. 2016, Fischer et al. 2010, Gehring et al. 2017). Given these circumstances, preventing un-characteristic disturbance in dry forests is probably the best option for maintaining current species distributions, especially on or near the trailing edge (Parks et al. 2019).

Resilience Implications

- Resilience to various disturbances (i.e. drought, fire, insects) is likely best created by heterogeneity in
  - Tree genetics (Fischer et al. 2010, Kolb et al. 2016)
  - Tree age diversity (Brown 2005, Baker & Williams 2015)
  - Spatial variation (Baker 2018)

Bryant et al. 2019 →