

Identifying and evaluating the effects of stand species composition  
on *Larix occidentalis* growth and development

Christian Mercado

11/24/2021

# 1 Introduction

Western larch (*Larix occidentalis* Nutt.) is an important tree species in the inland northwest region of the USA because of its contribution to ecological, economic, and cultural values across the region. *L. occidentalis* is endemic and nearly exclusive to the upper Columbia river watershed throughout Montana, Idaho, Washington, Oregon, and southern British Columbia, and is well-adapted to the historic climate of the region (Knudsen et al., 1968; Schmidt et al., 1976; Schmidt and McDonald, 1995). Additionally, its wood possesses desirable qualities such as high specific gravity, straight grains, and tight knots (Keegan III and Wichman, 1995), and it is the most productive of the three North American larch species (Rehfeldt and Jaquish, 2010), adding a unique and localized product value in the region. Further, western larch and its associated forests provide important habitat to native birds, bears, and ungulates (McClelland and McClelland, 1999; Schmidt et al., 1976). In a setting where fire is historically and currently prevalent, western larch is the most fire resistant of the Northern Rocky Mountain conifers due to its thick bark and uniquely deciduous needles (Schmidt et al., 1976). *Larix* species also provide unique aesthetic characteristics throughout the year with their phenology, coloring hillsides shades of green, yellow, and brown, depending on the season, adding a colorful representation of seasonality. However, projected climate scenarios are likely to impact the biophysical processes that allow larch to fill its niche within this region (Rehfeldt and Jaquish, 2010), threatening these unique values.

Across forests within the inland northwest, precommercial thinning (PCT) is a common, relatively low cost, and effective method to manage stand development and structure, either in response to or in the face of anthropogenic climate change. PCT can reduce inter-tree competition, increase individual volume growth, and promote structure that is conducive to higher yields (Hawley, 1921; Nyland, 2016; Oliver and Larson, 1996; Smith and Reukema, 1985). It can also have long-term impacts on height and diameter growth, as well as individual tree architecture (Harrington and Reukema, 1983; Weiskittel et al., 2009). Additionally, early thinning is cheaper and less logistically challenging than other intermediate activities, such as commercial thinning, herbicide treatment, and burning (Reukema, 1975). Furthermore, PCT can be an effective measure for producing forest structure that aids in fuels (Agee and Skinner, 2005; Dodge et al., 2019) and/or wildlife focused objectives (Hayes et al., 1997), making it a versatile management option with lasting, multi-purpose effects. Resulting structure in thinned-forests may also add to resistance and resilience in relation to climate change-aggravated disturbances and perturbations (Nagel et al., 2017). Lastly, PCT can be an effective method to maximize long-term carbon accumulation without sacrificing individual tree growth or understory development (Schaedel et al., 2017).

Density treatments in young stands can have short and long term impacts on western larch growth dynamics, as well as on overall stand development. Natural western larch seedling establishment tends to be very dense (many trees/unit area), and young densely-packed larch grow very quickly, making western larch stands ideal candidates for juvenile thinning (Schmidt et al., 1976; Schmidt, 1966; Schmidt and Seidel, 1988). Thompson (1992) found that thinning western larch early in stand development capitalizes on juvenile growth rates compared to thinning later in development. In a long-term study, Schaedel (2017) found that early density management can lead to larger tree size and stability over a rotation period. Additionally, different target PCT densities led to similar net stand yields over a rotation, suggesting that early thinning can control whether larch stand volume is concentrated in many smaller and less stable trees, or few larger, more stable (more commercially valuable) trees (Schaedel et al., 2017).

Western larch naturally grows across a compositional gradient of mixed-species forests (Schmidt and Seidel, 1988) where interactions among species attributes could impact growth and development at the individual- and stand-level. Western larch is classified as very intolerant of shade and one of the fastest-growing within its communities (Baker, 1949; Schmidt and Seidel, 1988). It is found in communities with: Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *glauca*), lodgepole pine (*Pinus contorta* (Dougl.)), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), ponderosa pine (*Pinus ponderosa*), western hemlock (*Tsuga heterophylla*), mountain hemlock (*Tsuga mertensiana*), and western redcedar (*Thuja plicata*) (Schmidt and Seidel, 1988; Schmidt and Shearer, 1981). These conifer species collectively span the range of shade tolerance and growth rates. A combination of shade-tolerance, height growth rate, water use efficiency, tree architecture, and other traits within mixed-species communities may lead to competitive

and/or complementary relationships among species (Forrester, 2017). Such mixing characteristics can result in altered species growth rates (Forrester, 2017), even from small differences in such traits (Riofrío et al., 2017). Lebourgeois (2013) found that species mixture modified the growth of *Abies alba* through facilitative interactions under drought conditions. In northwestern Montana, facilitative and competitive interactions were found to modify growth rates of *Abies lasiocarpa* and *Pinus albicaulis*, depending on environmental stressors (Callaway and Walker, 1997). Since larch forests range in species-composition and occur across environmental conditions, western larch may be subject to competitive or complementary relationships.

Evidence of how species-mixing impacts tree growth can shed light on relationships that are not currently well-understood if new research is expanded to more forest-types. Various studies in Europe have revealed that facilitation or competitive reduction in mixed-species stands can lead to enhanced productivity when compared to monocultures (Pretzsch and Schütze, 2009). This effect is sometimes termed overyielding, with reference to the potential for higher than anticipated biomass or volume (Pretzsch and Schütze, 2009). Further evidence suggests that mixture can interact with stand density in the long term, and that the interplay between the two likely depends on the characteristics of species-mixtures and stand types (Brunner and Forrester, 2020; Condés et al., 2013). In a study of *Abies grandis* (shade-tolerant) and *Pinus ponderosa* (shade-intolerant) mixtures in Oregon, USA, mixing impacted volume growth (only) at low spacing and was attributed to the light-use characteristics of each species (Maguire and Mainwaring, 2021). Vospernik (2021) found that individual tree basal area increment was significantly modified in mixtures of species with different traits, compared to mixtures of species with similar traits. Concerning larch, they observed mixing-effects on *Larix decidua* in mixtures with *Picea abies*, *Pinus cembra*, *Fagus sylvatica*, and *Betulus spp.*, where it mutually benefited in mixtures with *Picea abies* (Vospernik, 2021). These findings are similar to those of Zöhrer (1969) where incremental growth was increased in mixtures between shade-tolerant *Picea abies* and shade-intolerant *Larix decidua*. Interactions in communities of variable- and similar- trait species within North American *Larix* forests are not well-understood, and thus motivate further investigation to characterize how stand species composition modifies western larch growth dynamics.

## 2 Research Questions

Given the above, I am proposing the following lines of inquiry, hypotheses, and predictions:

### 2.1 *How does species-mixing impact basal area increment of western larch?*

Since there is evidence indicating that species-mixing can impact long-term development in temperate forests (Pretzsch et al., 2010; Pretzsch and Schütze, 2009; Zhang et al., 2012), I posit that the different physiological drivers motivating growth that relate to light interception (i.e. shade tolerance) within an interspecific environment can produce appreciable differences in the growth of a species, after accounting for tree size, site productivity, and stand density. This may happen through the enhancement of competition between species of similar shade-tolerance, or competitive reduction and/or facilitation between species of dissimilar shade-tolerance through niche complementarity (Callaway and Walker, 1997; Condés et al., 2013; Pretzsch et al., 2015; Riofrío et al., 2017). Further, I suggest that complementary or competitive effects of species traits in a stand can modify how a species interacts with stand density. For example, it is known that the density of western larch stands impacts how western larch grows (Schaedel et al., 2017). However, complementary or competitive interactions among species have not been acknowledged within this context, and may modify density effects on western larch growth, (e.g., a western larch in a high density stand may grow more in a mixture with shade-tolerant species than a western larch at the same density in a mixture with shade-intolerant species). I predict that the growth of western larch can respond to species-mixing across a gradient of species, depending on how its surrounding community interacts with light. Specifically, I presume *L. occidentalis* growth will be modified positively in mixtures with shade-tolerant species such as *Picea engelmannii*, *Abies grandis*, and *Abies lasiocarpa*. Conversely, I expect that *L. occidentalis* growth will be negatively impacted in mixtures with shade-intolerant *Pinus contorta* and *Pinus ponderosa*. I expect

that the roles of mid-tolerant species such as *Pseudotsuga menziesii* in modifying *L. occidentalis* growth will vary, from positive to negative, if mixing effects are present at all.

Therefore, my related research objectives are: (i) identify whether species-mixing has an effect on western larch growth, (ii) identify whether shade-tolerance, as a measure of interspecificity, captures the effects of mixing, (iii) quantify the degree to which species-mixing (defined by shade-tolerance) impacts basal area increment of western larch, and (iv) disentangle the the modifications that species-mixing may have on western larch growth at different densities.

## 2.2 *How does species-mixing modify the height-diameter allometry of western larch?*

Height is closely related to diameter and this relationship is subject to influences from attributes relating to stand structure, density, site quality, and competition (Sharma et al., 2019; Temesgen and Gadow, 2004). Since species-mixing modifies growth dynamics relating to these variables, and by the same logic presented above, I hypothesize that species-mixing can modify a species’s height-diameter relationship depending on mixture attributes. I presume, however, that the degree to which this occurs may depend on the level of competition. Thus, I predict that the height-diameter relationship of western larch will be modified by species mixture, but only in denser stands, where larch is mixed with shade-tolerants like *Picea engelmannii* and *Abies lasiocarpa*. Under these conditions, I expect western larch height will be greater due to mixing attributes, given size, site, and density remain unchanged. Similarly, I predict that western larch height will be less modified by species-mixture in lower density stands. Lastly, I predict that larch height will be lower in higher density stands when mixed with shade-intolerant species like *Pinus contorta* and *Pinus ponderosa*, given its size, site conditions, and density remain unchanged.

Thus, my research objectives are to: (v) identify whether species-mixing impacts the height-diameter relationship of western larch after accounting for other key variables, (vi) quantify the degree to which mixing affects western larch height-diameter allometry.

## 3 Proposed Methods & Timeline

### 3.1 PGP Data

The Forest Vegetation Simulator (FVS) is a distance-independent, individual tree forest growth model that is widely used in the western United States to predict tree and stand growth as well as to evaluate management decisions (Dixon, 2020). To establish a monitoring protocol for the FVS model, the USDA Forest Service Region 1 developed long-term permanent growth plot clusters (PGPs) in managed stands across the inland northwest (NW Montana and northern Idaho), referred herein to as the PGP program. The initial goal of the PGP program was to remeasure the selected stands at regular increments of 5-10 years in order to provide a robust growth increment data set. Various stand measurements were initialized and then remeasured between 1980 and 2002. The program was then paused, and was only recently revisited in 2018 and 2021, creating a wide gap between recent measurements and reducing consistency of measurement intervals.

Each PGP stand consists of 4 plot-clusters: 1 untreated control plot cluster and 3 treatment plot clusters, the latter were treated with commercial thinning or precommercial thinning, depending on stand age and maturity. Stand prescriptions determined target residual densities by species for the stand in the treatment areas, providing a side-by-side comparison between control and treatments under similar stand and site conditions. The location of control and treatment plots were determined by random selection of (x,y) coordinates on a grid laid over a map of the stand. To ensure that the control plots were not affected by nearby thinning, an unthinned buffer was placed around control clusters. Every cluster is comprised of three  $\sim 202m^2$  large-tree plots, with each plot containing three  $\sim 13.5 m^2$  small tree sub-plots. Data for trees in large-tree plots were taken based on whether a tree was above a specified diameter threshold. The diameter thresholds varied across and within stands (across control and treatment plots), as well as within clusters

over time. Yet the large trees were tagged and distance and azimuth to plot center were taken. Heights were taken on only a subset of large trees due to the operational challenges and added time of measuring tree height. Small tree data were recorded for trees greater than or equal to ~15cm in height from the ground, and up to the specified diameter threshold.

During the summer of 2018, a re-measurement campaign targeted various accessible stands with at least 3 previously recorded measurements on the Lolo National Forest. During the summer of 2021, PGP stands on the Lolo and Kootenai National Forests that were previously measured at least 3 times and that were composed of >50% overstory western larch (determined by most recent measurement) were targeted for remeasurement. Stands across the remeasured PGPs were spread between 46° N and 49° N, and between 800 and 1700 *m* above sea level. Stands were primarily on north-facing aspects. Soil conditions were variable from site-to-site, but most were a silty-loam texture. Species composition varied between almost pure western larch to mixed conifer forests composed of western larch, Douglas-fir, Engelmann spruce, grand fir, subalpine fir, western hemlock, mountain hemlock, western red cedar, cottonwood, and quaking aspen. Basic stand information is provided in Table 1.

Table 1: Stand Summary Table

| Stand ID       | National Forest | First Measurement | Last Measurement | Measurements | Elevation(m) | Aspect | Habitat Type                                    | Initial Disturbance           | % Basal Area Larch | Control Density (/ha) | Treatment Density (/ha) |
|----------------|-----------------|-------------------|------------------|--------------|--------------|--------|---|-------------------------------|--------------------|-----------------------|-------------------------|
| 01140109010001 | Kootenai        | 1987              | 2021             | 4            | 1494         | NE     | western hemlock/bride's bonnet-rusty menziesia  | Prescribed fire               | 100                | 1927                  | 6906                    |
| 01140119020008 | Kootenai        | 1983              | 2021             | 5            | 1524         | SE     | subalpine fir/bride's bonnet-bride's bonnet     | Scarification or Mech Logging | 84                 | 6096                  | 10131                   |
| 01140120010011 | Kootenai        | 1984              | 2021             | 5            | 1372         | W      | Douglas-fir/twinflower-common snowberry         | Scarification or Mech Logging | 54                 | 3378                  | 5881                    |
| 01140123030001 | Kootenai        | 1986              | 2021             | 5            | 1463         | NW     | subalpine fir/rusty menziesia                   | Scarification or Mech Logging | 81                 | 15847                 | 3914                    |
| 01140316020106 | Kootenai        | 1986              | 2021             | 5            | 884          | N      | Douglas-fir/common snowberry-pinegrass          | Prescribed fire               | 67                 | 8928                  | 1967                    |
| 01140343020046 | Kootenai        | 1983              | 2021             | 5            | 1494         | N      | subalpine fir/bride's bonnet                    | Prescribed fire               | 67                 | 7593                  | 1460                    |
| 01140528020011 | Kootenai        | 1986              | 2021             | 5            | 1006         | LR     | western hemlock/bride's bonnet-bride's bonnet   | Scarification or Mech Logging | 33                 | 13820                 | 7556                    |
| 01140588050005 | Kootenai        | 1987              | 2021             | 4            | 975          | SE     | western hemlock/bride's bonnet-bride's bonnet   | Prescribed fire               | 92                 | 3262                  | 368                     |
| 01160347060010 | Lolo            | 1986              | 2021             | 5            | 1707         | N      | subalpine fir/rusty menziesia                   | Logging                       | 18                 | 4811                  | 2076                    |
| 01160347060011 | Lolo            | 1986              | 2021             | 5            | 1615         | N      | subalpine fir/bride's bonnet-rusty menziesia    | Logging                       | 42                 | 8681                  | 2674                    |
| 01160410060004 | Lolo            | 1985              | 2021             | 5            | 1250         | NE     | western red cedar/bride's bonnet-bride's bonnet | Logging                       | 52                 | 10806                 | 2449                    |
| 01160415010059 | Lolo            | 1987              | 2021             | 4            | 1585         | NW     | grand fir/twinflower                            | Logging                       | 92                 | 8779                  | 4075                    |
| 01160708020064 | Lolo            | 1986              | 2018             | 4            | 1097         | NW     | grand fir/twinflower-twinflower                 | Logging                       | 4                  | 8419                  | 1648                    |
| 01160714020002 | Lolo            | 1985              | 2018             | 5            | 1524         | N      | western redecad/bride's bonnet-rusty menziesia  | Logging                       | 69                 | 20460                 | 26264                   |
| 01160734020002 | Lolo            | 1986              | 2018             | 4            | 1646         | NW     | mountain hemlock/rusty menziesia                | Logging                       | 81                 | 8369                  | 10252                   |
| 01160734020162 | Lolo            | 1988              | 2021             | 4            | 1554         | NW     | western red cedar/bride's bonnet                | Prescribed fire               | 58                 | 11928                 | 1873                    |
| 01160736010001 | Lolo            | 1989              | 2018             | 4            | 1280         | N      | western red cedar/bride's bonnet                | Logging                       | 70                 | 28911                 | 25753                   |
| 01160737010005 | Lolo            | 1986              | 2018             | 4            | 1463         | E      | grand fir/bride's bonnet-bride's bonnet         | Logging                       | 6                  | 12273                 | 2459                    |
| 01160739020139 | Lolo            | 1986              | 2018             | 4            | 1433         | NE     | western red cedar/bride's bonnet-bride's bonnet | Logging                       | 59                 | 25582                 | 5199                    |
| 01160764020036 | Lolo            | 1985              | 2018             | 5            | 1341         | W      | grand fir/twinflower                            | Logging                       | 6                  | 6590                  | 1725                    |

*Note:*

Habitat types are defined by Pfister et al. (1977).

All density metrics represent their value at time of first measurement.

Aspect classes are defined by direction in degrees(1-22=N, 23-67=NE, 68-112=E, 113-157=SE, 158-202=S, 203-247=SW,248-292=W, 293-337=NW, 338-360=N, and level/rolling =LR)

### 3.2 Proposed Analyses

I plan on utilizing a generalized additive model (GAM) framework to evaluate effects of predictors on periodic basal area increment (BAI) and height. This framework will follow that of Wykoff (1990) and Vospernik (2021), with GAMs used to select variables and examine predictor effects on the resulting modeled relationship. GAMs allow for flexibility in model fitting and an allowance for non-linear relationships across variables (Zhao et al., 2005). Contrary to traditional parametric modeling approaches, GAMs let the data determine the shape of the functional relationships by fitting predictors with smooth functions instead of specific parametric forms (Robinson et al., 2011).

The general strategy that I will follow consists of the following steps: (i) evaluating and estimating potential explanatory variables in the available data set based on established relationships with the dependent variable (BAI or height), (ii) sequentially selecting predictor variables with pre-determined groups through step-wise variable selection approaches to identify a base-model structure. Once a parsimonious base-model is selected, species-mixing variables will then be added to detect if there is a species-mixing effect. Further elaboration on applying this approach will be explained in the following text. The following equation represents the modeling framework:

$$g(E(Y)) = \beta_0 + f_1(x_1) + f_2(x_2) + \dots + f_i(x_i)$$

where  $g()$  represents a link function,  $E(Y)$  represents the expected value of a dependent variable ( $Y$ ) of interest,  $\beta_0$  represents an intercept, and  $f_i$  represents a non-linear function applied to an independent variable,  $x_i$ . In a case where a linear relationship between a predictor and the dependent variable exists, then a parametric formulation may be applied. For predictor variables displayed by groups, see Table 2.

Table 2: List of Potential Model Variables

| Size         | Site         | Competition              | Species Mixing            |
|--------------|--------------|--------------------------|---------------------------|
| Diameter     | Slope        | DBH:QMD Ratio            | Larch Basal Area Fraction |
| Height       | Aspect(°)    | Crown Competition Factor | Stand Shade Tolerance     |
| Basal Area   | Elevation    | BAL                      |                           |
| Crown Ratio  | Habitat-type | Trees Per Hectare        |                           |
| Crown Length |              | Stand Basal Area         |                           |

*Note:*

BAL - aggregate basal area of trees larger in diameter than the subject tree

QMD - Quadratic Mean Diameter

GAMs allow for the use of non-Gaussian conditional distributions for the dependent variable. I propose to use and compare a Gaussian distribution and a gamma distribution, with an appropriate link function. I will also consider natural log and square root link functions, depending on the distribution of BAI. However, careful consideration is required because the PGP data have a nested structure, e.g., measurements on trees within a cluster within a given measurement. The effects of this nesting can be captured within a mixed-effects model architecture, but my initial focus will be on the main effects (of each variable) on BAI prior to the introduction of random effects. I intend to explore mixed-model approaches as I continue to develop methodology.

#### 3.2.1 BAI Model

A common approach for characterizing BAI is to model it as a function of tree size, site characteristics, competition, and disturbance and management history (Vospernik, 2021; Wykoff, 1990). This approach

takes advantage of established biological and empirical relationships. It allows the flexibility to add and omit terms to enhance predictive ability and to detect sensitivity of the response to the predictors. Annual BAI can be calculated for a particular period by the following:

$$BAI_{ijt} = \frac{BA_{ij(t+1)} - BA_{ijt}}{A_{ij(t+1)} - A_{ijt}}$$

where  $BA_{ijt}$  is the basal area of a tree  $i$  within cluster  $j$  at a given measurement  $t$ ,  $BA_{ij(t+1)}$  is the basal area of the same tree at the next measurement  $(t + 1)$ , and  $A_{ijt}$  and  $A_{ij(t+1)}$  are the corresponding tree's ages. Therefore, the annual Basal Area Increment (BAI) of a tree is the difference in basal area of the same tree between two measurements, divided by the number of years between measurements.

I propose to initiate model development from these data through the variable and model selection process outlined above. Variables will be grouped by the following categories: size, site, competition, and species-mixing. An example of the initial GAM framework is shown below, where the conditional mean of BAI is given by:

$$g(E(BAI_{ijt})) = \beta_0 + f_1(Size_{ijt}) + f_2(Site_{jt}) + f_3(Competition_{ijt}) + f_4(Species - Mixing_{jt})$$

where  $BAI_{ijt}$  represents the BAI for a given tree  $i$  within cluster  $j$  at time  $t$ . Variables within each group are shown in Table 2.

A GAM will be used to assess individual partial responses for each predictor as in Vospernik (2021), where variables were selected group by group, and then compiled in a model. Variable selection will be performed on the resulting combined variable model. Predictors will be evaluated with information theoretic approaches such as Akaike's Information Criterion (AIC) and/or Schwarz's Information Criterion (BIC).

### 3.2.2 Height-Diameter Model

Tree height and diameter often hold a non-linear relationship, and prior work has identified how density modifies this relationship (Sharma et al., 2019; Staudhammer and LeMay, 2000; Temesgen and Gadow, 2004). Various functions have been used to described a relationship between height and diameter, and each holds merit under particular circumstances (Huang et al., 1992). However, instead of applying one function to the data, I will explore the relationship within the flexible GAM framework described above, where the data characterize the relationship without the necessity of *a priori* relationship assumptions, except for that of additivity. Diameter will be included first, followed by the addition of site and density terms by group, iteratively working through each. Once a combination of variables is selected and the main effects are accounted for, a species-mixing variable will be added and its effects will be analyzed. Variable selection will be made based on information theoretic approaches (AIC and/or BIC). The following characterizes the presumed model structure for evaluating the height-diameter relationship:

$$g(E(H_{ijt})) = \beta_0 + f_1(Diameter_{ijt}) + f_2(Site_{jt}) + f_3(Competition_{ijt}) + f_4(Species - mixing_{jt})$$

where  $H_{ijt}$  is the height of a given western larch  $i$  in cluster  $j$  at time  $t$ . Again, the subscript  $ijt$  denotes that effects of nesting may be present in the data due to the clustered sampling design, and further exploration of mixed-modeling approaches may be made.

### 3.2.3 Accounting for Species-Mixing

Species-mixing can be derived from the PGP data by different methods. Previous studies have determined species-mixing by the proportion of basal area of each species at initial measurement (Maguire and Mainwaring, 2021), stocking proportion, relative density, and weighted basal area proportions (Huber et al., 2014; Pretzsch and Schütze, 2009). The methods here mobilize similar ideas, as well as introduce the use of a



shade-tolerance metric to weigh the influence of species composition within a system. I propose the following approaches for assessing the potential contribution of species-mixing to growth and developmental characteristics.

1. Larch basal area fraction.

This is calculated simply as a ratio of basal area occupied by larch to basal area occupied by all species in a cluster at the time of the measurement:

$$L_{jt} = \frac{\sum_i BA_{ijt} I_{ijt}}{\sum_i BA_{ijt}} \quad I_{ijt} = \begin{cases} 1, & \text{if } i \text{ is western larch} \\ 0, & \text{otherwise} \end{cases}$$

where  $L_{jt}$  denotes the ratio,  $BA_{ijt}$  is the basal area of a tree  $i$ ,  $I_{ijt}$  is a binary operator which indicates whether a tree  $i$  is western larch ( $I_{ijt} = 1$ ), or otherwise ( $I_{ijt} = 0$ ).

2. Stand shade tolerance.

This is a weighted average of Lienard's shade tolerance index (Lienard et al., 2015):

$$T_{jt} = \frac{\sum_i \rho_{ijt} BA_{ijt}}{\sum_{ijt} BA_{ijt}}$$

where  $\rho_{ijt}$  represents the species specific shade-tolerance ranking of tree  $i$  (Lienard et al., 2015). This equation weights a species' abundance within a cluster by its level of shade tolerance (0, 0.25, 0.5, 0.75, 1), where 0 is shade-intolerant and 1 is very shade-tolerant (see Table 3).

Table 3: Shade tolerance for western conifers (Lienard et al., 2015)

| Genus              | Species             | Shade Tolerance |
|--------------------|---------------------|-----------------|
| <i>Larix</i>       | <i>occidentalis</i> | 0.00            |
| <i>Pinus</i>       | <i>contorta</i>     | 0.00            |
| <i>Pinus</i>       | <i>ponderosa</i>    | 0.25            |
| <i>Pinus</i>       | <i>monticola</i>    | 0.50            |
| <i>Pseudotsuga</i> | <i>menziesii</i>    | 0.50            |
| <i>Abies</i>       | <i>grandis</i>      | 0.75            |
| <i>Abies</i>       | <i>lasiocarpa</i>   | 0.75            |
| <i>Picea</i>       | <i>engelmannii</i>  | 0.75            |
| <i>Thuja</i>       | <i>plicata</i>      | 1.00            |
| <i>Tsuga</i>       | <i>heterophylla</i> | 1.00            |

### 3.3 Coursework and research activity thus far

I began my progress towards a master of science in forestry at the University of Montana in the Fall of 2020. The coursework that I have completed since is:

- STAT 451 - Statistical methods (3)
- STAT 457 - Statistics lab (1)
- FORS 594 - Graduate Seminar (1)
- FORS 697 - Research Credits (3)

- STAT 452 - Statistical methods 2 (3)
- FORS 540 - Disturbance Ecology (3)
- FORS 594 - Graduate Seminar: Silviculture (1)
- FORS 538 - Ecological Statistics (3)
- WILD 540 - Research Design (3)
- FORS 595 - Ecophysiology Seminar (2)

This coursework has primarily introduced me to methods of statistical analysis to be used in the ecological contexts. I've also had the opportunity to read about and discuss various topics relating to forestry, disturbance ecology, statistics, and ecophysiology in these courses.

During the summer of 2021, I led the field data collection effort on the PGP data set. I outreached, interviewed, and hired 3 excellent field technicians to work with during the summer. We successfully collected data in 13 PGP stands.

Prior to starting this program, I worked with the USDA Forest Service as a Forester with the Willamette National Forest, where I managed the small timber sales and special forest products permitting programs. I performed reconnaissance, drafted categorical exemptions, performed field data collection, appraisal, and contract preparation on timber sales. Additionally, I managed and issued permits relating to firewood, mushrooms, boughs, floral greens, and various other non-timber forest products.

I studied Forestry at Michigan State University, where I earned my Bachelor's of Science. I was born in Oregon, and grew up in Michigan.

## 3.4 Proposed Timeline

### 3.4.1 Data management and organization (December 2021-January 2022)

This includes the following tasks:

1. Writing scripts that clean and organize this extensive data set
2. Ensuring that available data are accessible and ready for analysis
3. Debugging and updating currently written scripts

I anticipate these tasks to provide some challenges, however, my fluency in R programming has excelled since I began here. Fortunately, some of this work has already been completed by myself and Dr. Affleck. This will be an ongoing effort throughout the entire thesis process, however, the bulk of it will occur during the time period listed above.

### 3.4.2 Data Analysis (January 2022 – April 2022)

1. Exploring the topics and methods provided above
2. Applying the proposed methodology to the PGP data set
3. Summarizing findings in a format that is ready for publication

I anticipate learning more about the proposed methodology and its applications prior to implementing them. I think that my hypotheses could face challenges that will require me to think further into how trees grow and develop. Distilling the data into easily-digestible format which is ready to be written about will likely take time and thought that beyond anything that I've done before.

### **3.4.3 Thesis Composition and Manuscript Preparation (March 2022 – June 2022)**

This includes the actual drafting, formatting, summarizing, etc. of these data for the purpose of communicating what I did, how I did it, the outcomes of the study, and how it fits into the broader picture that is forest ecology and science. These tasks, again, will provide some amount of novelty to me, and will likely take more time than I expect, since I have never performed or communicated novel research to date.

I anticipate and hope that my work may be worthy of publication, so long as my findings can make a valuable contribution to the corpus of forest ecological science and modeling. I am sure that the efforts revolving around and concise communication of my research will present various challenges to me that I have not even thought about yet.

### **3.4.4 Defense (June 2022)**

My defense will require that I have done nearly all of the above tasks and distill the entire process into a format that is communicable, comprehensive, concise, and intelligible. I expect this to be a great challenge, but look forward to the prospect of communicating about what I have worked on throughout the MS degree-seeking process.

## References

- Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* 211, 83–96. <https://doi.org/10.1016/j.foreco.2005.01.034>
- Baker, F., 1949. A Revised Tolerance Table. *Journal of Forestry* 47, 179–181. <https://doi.org/10.1093/jof/47.3.179>
- Brunner, A., Forrester, D.I., 2020. Tree species mixture effects on stem growth vary with stand density: An analysis based on individual tree responses. *Forest Ecology and Management* 473, 118334. <https://doi.org/10.1016/j.foreco.2020.118334>
- Callaway, R.M., Walker, L.R., 1997. Competition and facilitation: A synthetic approach to interactions in plant communities. *Ecology* 78, 1958–1965. [https://doi.org/10.1890/0012-9658\(1997\)078%5B1958:CAFASA%5D2.0.CO;2](https://doi.org/10.1890/0012-9658(1997)078%5B1958:CAFASA%5D2.0.CO;2)
- Condés, S., Del Rio, M., Sterba, H., 2013. Mixing effect on volume growth of *Fagus sylvatica* and *Pinus sylvestris* is modulated by stand density. *Forest Ecology and Management* 292, 86–95. <https://doi.org/10.1016/j.foreco.2012.12.013>
- Dixon, G.E., 2020. Essential FVS : A User's Guide to the Forest Vegetation Simulator (Revised). USDA Forest Service, Forest Management Center, Fort Collins, CO.
- Dodge, J.M., Strand, E.K., Hudak, A.T., Bright, B.C., Hammond, D.H., Newingham, B.A., 2019. Short- and long-term effects of ponderosa pine fuel treatments intersected by the Egley Fire Complex, Oregon, USA. *Fire Ecology* 15. <https://doi.org/10.1186/s42408-019-0055-7>
- Forrester, D.I., 2017. Ecological and physiological processes in mixed versus monospecific stands. *Mixed-Species Forests: Ecology and Management* 73–115. [https://doi.org/10.1007/978-3-662-54553-9\\_3](https://doi.org/10.1007/978-3-662-54553-9_3)
- Harrington, C.A., Reukema, D.L., 1983. Initial Shock and long-term stand development following thinning in a Douglas-fir Plantation. *Forest Science* 29, 33–46.
- Howley, R.C., 1921. The practice of silviculture, with particular reference to its application in the United States. John Wiley & sons, Incorporated, 1921. <https://doi.org/10.5962/bhl.title.55736>
- Hayes, J.P., Chan, S.S., Emmingham, W.H., Tappeiner, J.C., Kellogg, L.D., Bailey, J.D., 1997. Wildlife response to thinning young forests in the Pacific Northwest. *Journal of Forestry* 95, 28–33. <https://doi.org/10.1093/jof/95.8.28>
- Huang, S., Titus, S.J., Wiens, D.P., 1992. Comparison of nonlinear height-diameter functions for major Alberta tree species. *Canadian Journal of Forest Research* 22, 1297–1304. <https://doi.org/10.1139/x92-172>
- Huber, M.O., Sterba, H., Bernhard, L., 2014. Site conditions and definition of compositional proportion modify mixture effects in *Picea abies*-*Abies alba* stands. *Canadian Journal of Forest Research* 44, 1281–1291. <https://doi.org/10.1139/cjfr-2014-0188>
- Keegan III, C.E., Wichman, D.P., 1995. Use and Value of Western Larch as a Commercial Timber Species, in: *Ecology and Management of Larix Forests: A Look Ahead: Proceedings of an International Symposium*, Whitefish, Montana, USA October 5-9, 1992. US Department of Agriculture, Forest Service, Intermountain Research Station, p. 155.
- Knudsen, G.M., Arno, S.F., Habeck, J.R., Blake, G.M., 1968. Natural Distribution of Western Larch and Subalpine Larch, Research Note 7. University of Montana, Missoula, Montana.
- Lebourgeois, F., Gomez, N., Pinto, P., Mérian, P., 2013. Mixed stands reduce *Abies alba* tree-ring sensitivity to summer drought in the Vosges mountains, western Europe. *Forest Ecology and Management* 303, 61–71. <https://doi.org/10.1016/j.foreco.2013.04.003>
- Lienard, J., Florescu, I., Strigul, N., 2015. An appraisal of the classic forest succession paradigm with the shade tolerance index. *PLoS ONE* 10, 1–22. <https://doi.org/10.1371/journal.pone.0117138>

- Maguire, D.A., Mainwaring, D.B., 2021. Effects of initial spacing and species mix on stand developmental patterns in two field trials in central Oregon. *Forest Ecology and Management* 491, 119153. <https://doi.org/10.1016/j.foreco.2021.119153>
- McClelland, B.R., McClelland, P.T., 1999. Pileated woodpecker nest and roost trees in Montana: Links with old-growth and forest "health". *Wildlife Society Bulletin* 27, 846–857.
- Nagel, L.M., Palik, B.J., Battaglia, M.A., D'Amato, A.W., Guldin, J.M., Swanston, C.W., Janowiak, M.K., Powers, M.P., Joyce, L.A., Millar, C.I., Peterson, D.L., Ganio, L.M., Kirschbaum, C., Roske, M.R., 2017. Adaptive silviculture for climate change: A national experiment in manager-scientist partnerships to apply an adaptation framework. *Journal of Forestry* 115, 167–178. <https://doi.org/10.5849/jof.16-039>
- Nyland, R.D., 2016. *Silviculture: Concepts and Applications*, Third. ed. Waveland Press, Inc.
- Oliver, C.D., Larson, B.A., 1996. *Forest stand dynamics*, Updated Edition. John Wiley & sons, Incorporated, 1921.
- Pfister, R.D., Kovalchik, B.L., Arno, S.F., Presby, R.C., 1977. Forest habitat types of Montana (No. INT-GTR-34). USDA Forest Service, Intermountain Forest & Range Experiment Station, Ogden, Utah.
- Pretzsch, H., Block, J., Dieler, J., Dong, P.H., Kohnle, U., Nagel, J., Spellmann, H., Zingg, A., 2010. Comparison between the productivity of pure and mixed stands of Norway spruce and European beech along an ecological gradient. *Annals of Forest Science* 67, 712–712. <https://doi.org/10.1051/forest/2010037>
- Pretzsch, H., del Río, M., Ammer, C., Avdagic, A., Barbeito, I., Bielak, K., Brazaitis, G., Coll, L., Dirnberger, G., Drössler, L., Fabrika, M., Forrester, D.I., Godvod, K., Heym, M., Hurt, V., Kurylyak, V., Löf, M., Lombardi, F., Matović, B., Mohren, F., Motta, R., den Ouden, J., Pach, M., Ponette, Q., Schütze, G., Schweig, J., Skrzyszewski, J., Sramek, V., Sterba, H., Stojanović, D., Svoboda, M., Vanhellemont, M., Verheyen, K., Wellhausen, K., Zlatanov, T., Bravo-Oviedo, A., 2015. Growth and yield of mixed versus pure stands of Scots pine (*Pinus sylvestris* L.) And European beech (*Fagus sylvatica* L.) Analysed along a productivity gradient through Europe. *European Journal of Forest Research* 134, 927–947. <https://doi.org/10.1007/s10342-015-0900-4>
- Pretzsch, H., Schütze, G., 2009. Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: Evidence on stand level and explanation on individual tree level. *European Journal of Forest Research* 128, 183–204. <https://doi.org/10.1007/s10342-008-0215-9>
- Rehfeldt, G.E., Jaquish, B.C., 2010. Ecological impacts and management strategies for western larch in the face of climate-change. *Mitigation and Adaptation Strategies for Global Change* 15, 283–306. <https://doi.org/10.1007/s11027-010-9217-2>
- Reukema, D.L., 1975. Guidelines for Precommercial Thinning of Douglas-Fir (No. PNW-GTR-030). USDA Forest Service, Pacific Northwest Research Station, Portland, OR.
- Riofrío, J., Del Río, M., Bravo, F., 2017. Mixing effects on growth efficiency in mixed pine forests. *Forestry* 90, 381–392. <https://doi.org/10.1093/forestry/cpw056>
- Robinson, A.P., Lane, S.E., Thérien, G., 2011. Fitting forestry models using generalized additive models: A taper model example. *Canadian Journal of Forest Research* 41, 1909–1916. <https://doi.org/10.1139/x11-095>
- Schaedel, M.S., Larson, A.J., Affleck, D.L.R., Belote, R.T., Goodburn, J.M., Wright, D.K., Sutherland, E.K., 2017. Long-term precommercial thinning effects on *Larix occidentalis* (western larch) tree and stand characteristics. *Canadian Journal of Forest Research* 47, 861–874. <https://doi.org/10.1139/cjfr-2017-0074>
- Schmidt, W.C., 1966. Growth opportunities for young western larch (No. Research Note INT-50). USDA Forest Service, Intermountain Forest & Range Experiment Station, Ogden, Utah.
- Schmidt, W.C., McDonald, K.J., 1995. Ecology and management of *Larix* forests: A look ahead... *Proceedings of an International Symposium* (No. Conference Proceedings). USDA Forest Service.

- Schmidt, W.C., Seidel, K.W., 1988. Western larch and space: Thinning to optimize growth. In *Future Forests of the Mountain West: A Stand Culture Symposium*. (No. General Technical Report INT-243). USDA Forest Service, Intermountain Research Station, Ogden, Utah.
- Schmidt, W.C., Shearer, R.C., 1981. *Larix occidentalis*: A pioneer of the North American West General Technical Report INT 33, in: Ecology and Management of Larix Forests: A Look Ahead. pp. 33–37.
- Schmidt, W.C., Shearer, R.C., Roe, A.L., 1976. Ecology and Silviculture of Western Larch Forests (No. 1516), Technical Bulletin, Forest Service, US Department of Agriculture. USDA Forest Service.
- Sharma, R.P., Vacek, Z., Vacek, S., Kučera, M., 2019. Modelling individual tree heightdiameter relationships for multi-layered and multi-species forests in central Europe. *Trees - Structure and Function* 33, 103–119. <https://doi.org/10.1007/s00468-018-1762-4>
- Smith, J.H.G., Reukema, D.L., 1985. Effects of plantation and juvenile spacing on tree and stand development, in: Effects of Plantation and Juvenile Spacing on Tree and Stand Development. College of Forest Resources, University of Washington, Seattle, WA, pp. 239–245.
- Staudhammer, C., LeMay, V., 2000. Height prediction equations using diameter and stand density measures. *Forestry Chronicle* 76, 303–309. <https://doi.org/10.5558/tfc76303-2>
- Temesgen, H., Gadow, K. v., 2004. Generalized height-diameter models - An application for major tree species in complex stands of interior British Columbia. *European Journal of Forest Research* 123, 45–51. <https://doi.org/10.1007/s10342-004-0020-z>
- Thompson, C.F., 1992. Crop tree thinning of western larch in southeastern British Columbia: 30-year results (No. Research Note 110). BC Ministry of Forests, Nelson, BC.
- Vospernik, S., 2021. Basal area increment models accounting for climate and mixture for Austrian tree species. *Forest Ecology and Management* 480, 118725. <https://doi.org/10.1016/j.foreco.2020.118725>
- Weiskittel, A.R., Kenefic Laura S., L.S., Seymour, R.S., Phillips, L.M., 2009. Long-term effects of precommercial thinning on the stem dimensions, form and branch characteristics of red spruce and balsam fir crop trees in Maine, USA. *Silva Fennica* 43, 397–409. <https://doi.org/10.14214/sf.196>
- Wykoff, W.R., 1990. A basal area increment model for individual conifers in the northern Rocky Mountains. *Forest Science* 36, 1077–1104. <https://doi.org/10.1093/forestscience/36.4.1077>
- Zhang, Y., Chen, H.Y.H., Reich, P.B., 2012. Forest productivity increases with evenness, species richness and trait variation: A global meta-analysis. *Journal of Ecology* 100, 742–749. <https://doi.org/10.1111/j.1365-2745.2011.01944.x>
- Zhao, D., Wilson, M., Borders, B.E., 2005. Modeling response curves and testing treatment effects in repeated measures experiments: A multilevel nonlinear mixed-effects model approach. *Canadian Journal of Forest Research* 35, 122–132. <https://doi.org/10.1139/x04-163>
- Zöhrer, F., 1969. Bestandeszuwachs und Leistungsvergleich montan-subalpiner Lärchen-Fichten-Mischbestände. *Forstwissenschaftliches Centralblatt* 88, 41–63. <https://doi.org/10.1007/BF02741762>