

Identifying and evaluating the effects of forest composition and  
mixing on *Larix occidentalis* growth and development

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# 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, even 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, 1986). 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., 1996), 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., 2017a).

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 (2017b) 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 and more stable trees (Schaedel et al., 2017b).

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), which 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, termed overyielding (Pretzsch and Schütze, 2009). Further evidence provides the notion 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 require further investigation to characterize how inter-specificity modifies tree 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. 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). 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 explaining interspecificity, captures the effects of mixing, and (iii) quantify the degree to which species-mixing (defined by shade-tolerance) impacts basal area increment of western larch.

## 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 more on the level of complementarity than 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*. Contrarily, I predict that western larch height-diameter will be less impacted by species-mixture in lower density stands, as well as in higher density stands when mixed with shade-intolerant species like *Pinus contorta* and *Pinus ponderosa*.

Furthermore, my related research objectives are: (iv) identify whether species-mixing impacts the height-diameter relationship of western larch in isolation of other variables, (v) quantify the degree to which mixing has on western larch height-diameter allometry.

### 3 Proposed Methods & Timeline

#### 3.1 PGP Data

Table 1: Stand Summary Table

Stand ID	National Forest	First Measurement	Last Measurement	Measurements	Elevation(m)	Aspect	Habitat Type	Initial Disturbance	% BA Larch	Control Density (tph)	Treatment Density (tph)
01140109010001	Kootenai	1987	2021	3	1494	NE	western hemlock/bride's bonnet-rusty menziesia	Prescribed fire	100	1927	6906
01140119020008	Kootenai	1983	2021	4	1524	SE	subalpine fir/bride's bonnet-bride's bonnet	Scarification or Mech Logging	84	6096	10131
01140120010011	Kootenai	1984	2021	4	1372	W	Douglas-fir/twinflower-common snowberry	Scarification or Mech Logging	54	3378	5881
01140123030001	Kootenai	1986	2021	4	1463	NW	subalpine fir/rusty menziesia	Scarification or Mech Logging	81	15847	3914
01140316020106	Kootenai	1986	2021	4	884	N	Douglas-fir/common snowberry-pinegrass	Prescribed fire	67	8928	1967
01140343020046	Kootenai	1983	2021	4	1494	N	subalpine fir/bride's bonnet	Prescribed fire	67	7593	1460
01140528020011	Kootenai	1986	2021	4	1006	LR	western hemlock/bride's bonnet-bride's bonnet	Scarification or Mech Logging	33	13820	7556
01140588050005	Kootenai	1987	2021	3	975	SE	western hemlock/bride's bonnet-bride's bonnet	Prescribed fire	92	3262	368
01160347060010	Lolo	1986	2021	4	1707	N	subalpine fir/rusty menziesia	Logging	18	4811	2076
01160347060011	Lolo	1986	2021	4	1615	N	subalpine fir/bride's bonnet-rusty menziesia	Logging	42	8681	2674
01160410060004	Lolo	1985	2021	4	1250	NE	western red cedar/bride's bonnet-bride's bonnet	Logging	52	10806	2449
01160415010059	Lolo	1987	2021	3	1585	NW	grand fir/twinflower	Logging	92	8779	4075
01160708020064	Lolo	1986	2018	3	1097	NW	grand fir/twinflower-twinflower	Logging	4	8419	1648
01160714020002	Lolo	1985	2018	4	1524	N	western recedar/bride's bonnet-rusty menziesia	Logging	69	20460	26264
01160734020002	Lolo	1986	2018	3	1646	NW	mountain hemlock/rusty menziesia	Logging	81	8369	10252
01160734020162	Lolo	1988	2021	3	1554	NW	western red cedar/bride's bonnet	Prescribed fire	58	11928	1873
01160736010001	Lolo	1989	2018	3	1280	N	western red cedar/bride's bonnet	Logging	70	28911	25753
01160737010005	Lolo	1986	2018	3	1463	E	grand fir/bride's bonnet-bride's bonnet	Logging	6	12273	2459
01160739020139	Lolo	1986	2018	3	1433	NE	western red cedar/bride's bonnet-bride's bonnet	Logging	59	25582	5199
01160764020036	Lolo	1985	2018	4	1341	W	grand fir/twinflower	Logging	6	6590	1725

*Note:*

Habitat types are defined by (Pfiester et al., 1977). All density metrics represent their value at time of first measurement

The Forest Vegetation Simulator (FVS) is a distance-independent, individual tree forest growth model that is widely used in the United States to predict tree and stand growth and 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 (PGP's) in managed stands across the inland northwest US (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 measured and then remeasured between 1980 and 2002. The program was then paused, and was only recently revisited in 2018 and 2021, creating wide gap between 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 which were treated with commercial thinning or precommercial thinning, depending on stand age and maturity. Every cluster is comprised of three-  $\sim 202m^2$  large-tree plots, with each plot containing three-  $\sim 13.5m^2$  small tree sub-plots. Data for trees in large-tree plots were taken based on whether a tree was within a plot and if it 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. These trees were tagged, distance and azimuth to plot center were taken. Additionally, heights were not taken on all large trees due to the operational challenges and added time of measuring tree height. Small tree data were recorded for trees above greater than or equal to  $\sim 15.24cm$  in height from the ground, and up to the specified diameter threshold. 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 un-thinned buffer was placed around control clusters.

During the summer of 2018, a re-measurement campaign was conducted and 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 PGP's were variable, spread between  $46^\circ N$  and  $49^\circ N$ , 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 WL dominant forests 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.

## 3.2 Proposed Analyses

I plan on utilizing a generalized additive model (GAM) framework to evaluate effects of predictors on BAI and Height. This framework will loosely follow that of Vospernik (2021), where GAMs will be 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 different variables (Zhao et al., 2005). Contrary to traditional parametric modeling approaches, GAMs let the data determine the shape of the model through fitting predictors with smooth functions instead of specifying detailed parameters for each variable (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) iteratively selecting variables by groups through step-wise variable selection approach to select a base-model structure. Once a parsimonious base-model is selected, (iii) a species-mixing variable will then be added to detect if there is a species-mixing effect, then (iv) the model will be analyzed to characterize the mixing effect (if present). Further elaboration on applying this approach will be explained in the following text. The following equation represents the outlined framework:

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

where  $g()$  represents some link function,  $E(Y)$  represents the expected value of a dependent variable 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 variables displayed by groups, see Table 2.

Table 2: List of Potential Model Variables

Size	Site	Density	Competition	Species Mixing
Diameter	Dominant Height	Trees Per Hectare	DBH:QMD Ratio	Initial proportion of Western Larch (BA)
Height	Slop	Stand Basal Area	Crown Competition Factor	Shade Tolerance Index
Basal Area	Aspect		BAL (Basal area of trees larger than the subject tree)	Crown Ratio Index
	Elevation			Crown Length Index
	Habitat-type			

### 3.2.1 BAI Model

A common approach for characterizing BAI is through modeling 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 empirical relationships and 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:

$$BAI = \frac{BA_{m+1} - BA_m}{(m+1) - m}$$

where  $BA_{ijt}$  is the basal area of a tree  $i$  within a cluster  $j$  at a given measurement year  $t$ ,  $BA_{ij(t+1)}$  is the basal area of the same tree at the next subsequent measurement ( $t+1$ ). 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, and thus is expressed as BAI, where the increment is 1 year.

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:

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

where  $BAI_{ijt}$  represents the BAI for a given tree  $i$  within cluster  $j$  at time  $t$ , and  $\epsilon_{ijk}$  represents random effects within a given tree  $i$  in a given cluster  $j$  at time  $t$ . Variables within each group are shown in 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. However, careful consideration is required because the PGP data are nested within a data 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. Predictors will be evaluated with implementing 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:

$$g(E(\text{Height}_{ijt})) = \beta_0 + f_1(\text{Diameter}_{ijt}) + f_2(\text{Site}_{jt}) + f_3(\text{Density}_{jt}) + f_4(\text{Competition}_{ijt}) + f_5(\text{Species} - \text{mixing}_{jt})$$

where  $\text{Height}_{ijt}$  is the predicted 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 [Maguire2020], 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. Time 1 species composition – relative abundance of larch within a cluster.

This is calculated simply as a ratio of basal area occupied by larch in a cluster to basal area occupied by non-larch in a cluster at the time of the measurement.

$$\frac{\sum BA_{jt,WL}}{\sum BA_{jt,Other}}$$

where  $BA_{jt,WL}$  is the cluster sum of basal area of western larch and  $BA_{Other,jt}$  is the total cluster basal area of all non-larch species.

2. Species composition weighted by shade tolerance.

This is represented by Lienard’s shade tolerance index (Lienard et al., 2015), modified to represent the shade-tolerance of a measurement plot cluster in these data, as shown here:

$$\delta_{sjt} = \frac{\sum_{s=1} \rho_s BA_{sjt}}{\sum_{s=1} BA_{sjt}}$$

where  $\delta_{jt}$  is the shade tolerance index for a cluster  $j$ ,  $\sum_{s=1}$  represents the summation over species  $s$  through all species present,  $\rho_s$  represents the shade-tolerance ranking of a species (Lienard et al., 2015), and  $BA_{sjt}$  represents the cluster-level  $j$  basal area value for a species  $s$  at time of measurement  $t$ . 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 not shade-tolerant and 1 is very shade-tolerant.

## 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
- STAT 457 - Statistics lab
- FORS 594 - Graduate Seminar
- FORS 697 - Research Credits
- STAT 452 - Statistical methods 2
- FORS 540 - Disturbance Ecology
- FORS 594 - Graduate Seminar: Silviculture
- FORS 538 - Ecological Statistics
- WILD 540 - Research Design
- FORS 595 - Ecophysiology Seiminar

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 is 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.

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

This will come with its challenges and obstacles. I anticipate learning more about these proposed methodology and the application 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.

#### Composition (March 2022 – May 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.

#### Manuscript Preparation (May 2022-??)

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 modelling. 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.

#### 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.

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