2020

Long-term Effects of Crop-tree Release on the Growth and Quality of Upland White Oak Stands

Philip Jay Vogel
University of Kentucky, philipjayvogel@gmail.com
Digital Object Identifier: https://doi.org/10.13023/etd.2020.144

Recommended Citation

Vogel, Philip Jay, "Long-term Effects of Crop-tree Release on the Growth and Quality of Upland White Oak Stands" (2020). *Theses and Dissertations--Forestry and Natural Resources*. 53.
https://uknowledge.uky.edu/forestry_etds/53

STUDENT AGREEMENT:

I represent that my thesis or dissertation and abstract are my original work. Proper attribution has been given to all outside sources. I understand that I am solely responsible for obtaining any needed copyright permissions. I have obtained needed written permission statement(s) from the owner(s) of each third-party copyrighted matter to be included in my work, allowing electronic distribution (if such use is not permitted by the fair use doctrine) which will be submitted to UKnowledge as Additional File.

I hereby grant to The University of Kentucky and its agents the irrevocable, non-exclusive, and royalty-free license to archive and make accessible my work in whole or in part in all forms of media, now or hereafter known. I agree that the document mentioned above may be made available immediately for worldwide access unless an embargo applies.

I retain all other ownership rights to the copyright of my work. I also retain the right to use in future works (such as articles or books) all or part of my work. I understand that I am free to register the copyright to my work.

REVIEW, APPROVAL AND ACCEPTANCE

The document mentioned above has been reviewed and accepted by the student's advisor, on behalf of the advisory committee, and by the Director of Graduate Studies (DGS), on behalf of the program; we verify that this is the final, approved version of the student's thesis including all changes required by the advisory committee. The undersigned agree to abide by the statements above.

Philip Jay Vogel, Student

Dr. John M. Lhotka, Major Professor

Dr. Steven J. Price, Director of Graduate Studies

LONG-TERM EFFECTS OF CROP-TREE RELEASE ON THE GROWTH AND QUALITY OF UPLAND WHITE OAK STANDS

THESIS

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science in Forest and Natural Resource Sciences
in the College of Agriculture, Food and Environment
at the University of Kentucky

By

Philip Jay Vogel

Lexington, Kentucky

Director: Dr. John M. Lhotka, Professor of Silviculture

Lexington, Kentucky

2020

ABSTRACT OF THESIS

LONG-TERM EFFECTS OF CROP-TREE RELEASE ON THE GROWTH AND QUALITY OF UPLAND WHITE OAK STANDS

The alteration of historical disturbance regimes, forest parcelization, and varying goals among landowners all present challenges to oak management in the eastern U.S. Foresters and landowners need tools to promote oak sustainability that are applicable on small forestland holdings and within complex management plans. From this perspective, this research evaluates a crop-tree release study installed in southeastern Kentucky in 1983. The experiment includes four, 2-acre replications of three treatment levels: 20 crop-trees per acre, 34 crop-trees per acre, and a control treatment in which crop-trees were selected but not released. Half-acre measurement plots were installed at the outset of the study. Crown class, dbh, and crop-tree grade were measured in year 0, 5, 10, 17, and 35 following treatment. Using these data, two facets of crop-tree release were analyzed: 1) how a crop-tree release affects white oak crop-trees in terms of tree growth rate and stem quality, 2) how a crop-tree release alters stand structure and per acre volume and value. Results indicate that crop-tree release applied to small sawtimber sized stands increases crop-tree diameter growth and the proportion of crop-trees reaching their maximum potential grade while promoting stand-wide growth.

KEYWORDS: *Quercus alba*, crop-tree release, oak silviculture, eastern U.S.

Philip Jay Vogel

May 11, 2020

LONG-TERM EFFECTS OF CROP-TREE RELEASE ON THE GROWTH AND QUALITY OF UPLAND WHITE OAK STANDS

By

Philip Jay Vogel

Dr. John M. Lhotka

Director of Thesis

Dr. Steven J. Price

Director of Graduate Studies

May 8, 2020

To Olivia,

who listened to me talk

about crop-tree release

too much

ACKNOWLEDGMENTS

First and foremost, I want to express my sincere gratitude to my advisor, Dr. John Lhotka, for consistently providing thorough and helpful guidance concerning the research presented in this work. I would also like to thank my graduate committee members, Dr. Jeffrey Stringer, who established, preserved, and continued this study, and Dr. Thomas Ochuodho, who helped me navigate the confusing world of economics. For funding, I would like to recognize the University of Kentucky Department of Forestry and Natural Resources as well as the USDA McIntire-Stennis Cooperative Forestry Research Program. I am indebted to Zachary Hackworth, who provided counsel in the lab and assistance in the field throughout this project, saving me countless hours of confusion. In addition, I would like to thank Joe Frederick, Wendy Leuenberger, David Collett, and Dr. Jeffrey Stringer for assisting in data collection.

I would also like to thank my family, who have provided love and support throughout the years. My mother instilled in me an appreciation of nature and my father spent many hours helping me make graphs for science fair projects. Both of these gifts have helped me immensely over the last two years. My siblings have listened to me talk about trees a lot, and they have even cared a little about some of it. My wife, Olivia, has shown patience and love, and has made certain that I continue to sleep, eat, and maintain perspective. I would also like to thank Bob Dylan for writing the lyric: "It's not dark yet, but it's getting there," which has provided me consolation throughout this endeavor. And finally, I would like to acknowledge the Creator: "He watereth the hills from his chambers: the earth is satisfied with the fruit of thy works."

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: INTRODUCTION

1.1 White Oak in the Holocene Epoch

The fate of the forest across the eastern U.S. has been interwoven throughout history with human land uses. For as long as mankind has made a life for himself in the region, he has also been a part of the forces—whether by chance or by choice—that make the forest. Paleo-ecological studies suggest that oak (*Quercus*) has been the dominant genus in forests across the eastern U.S. throughout the Holocene epoch. In the wake of the glacial retreat, a combination of biotic and abiotic pressures allowed oak—and white oak (*Quercus alba*) in particular—to thrive (Abrams 2003).

Early botanists, likely embellishing, claimed that white oak comprised 9/10th of some forests (Abrams 2003). While it may be an exaggeration, the claim does highlight the spread and ubiquity of white oak in the eastern U.S. prior to European settlement. Although white oak saw its peak dominance in oak-hickory and oak-pine forest types, it could be found in every major deciduous forest in the eastern U.S. The species exhibited a broad range, occurring in every state east of the Central Plains, and could be found in wet-mesic to sub-xeric habitats. In nearly all parts of its range, a few species could occupy rockier, drier, more nutrient-deprived sites. For example, chestnut oak (*Quercus montana*), northern red oak (*Quercus rubra*), and American chestnut (*Castanea dentata*) exhibited more importance than white oak on high-elevation, rocky ridges in the Appalachians mountains. In contrast, many species could better thrive in wetter sites. Regardless, white oak dominated forests in the southern parts of the Northeastern states, in the Midwest and Central states, and especially in the Mid-Atlantic states. It also accounted for a significant portion of the forest throughout the Piedmont and the Central and Southern Appalachians, though not the Deep South, and in the Southern and Central regions of the Lake states (Abrams 2003).

The glacial retreat brought a warmer, drier climate with an associated increase in fire frequency. Combined with the land-use patterns of Native Americans, which included land clearing, burning, and agriculture, these environmental changes provided the perfect conditions for white oak to thrive (Abrams 2003). White oak possesses a suite of traits suited for persisting through drought and fire, but not dense understory conditions (Abrams 2003). White oak preferentially allocates carbohydrates to root growth. Their extensive root systems allow them to combat drought by maintaining a high predawn shoot water potential after overnight rehydration. Additionally, they have developed tissue-water relationships to allow for high rates of gas exchange while avoiding desiccation. These include low osmotic potential, low relative water content at zero turgor, and low water potential threshold for stomatal closure (Abrams 1990). Their deep roots also contribute to white oak seedlings' vigorous sprouting ability after dieback caused by fire. More mature white oaks respond well to fire damage because they produce tyloses, idiosyncratic outgrowths of cell walls that help compartmentalize wounds (Abrams 2003). While deep and extensive root systems give white oaks an advantage in the face of drought and fire, their strategy to allocate carbohydrates in this manner puts them in a vulnerable position in dense understories. Although they produce large acorns that provide high initial shoot growth, height growth typically slows after the first year (Cho and Boerner 1991). In forests where white oak seedlings compete in the understory with abundant shade-tolerant species, a severe bottleneck between white oak seedlings and white oak saplings is often apparent (Nowacki et al. 1990). However, in forests with sparse understories, the intermediate shade tolerance of white oak allows it to persist in the understory for up to 100 years until a gap appears in the overstory into which it can grow (Abrams 2003).

Prior to European settlement, the historical record suggests that forest conditions were conducive to sustaining white oak. The species tends to persist under a regime of recurring low-intensity disturbances with periodic fires that maintain favorable understory conditions (Abrams 2003). Prior to declines in Native American populations in the eastern U.S. associated with European settlement, the mean fire frequency ranged from 2 years—sometimes less—in the South to 50-100 years in the Northeast with fire free intervals ranging from 1-100 years (Dey 2014). This pattern of periodic fire followed by sometimes extended fire free intervals maintained ideal forest conditions for white oak by keeping the population of fire-sensitive, late-successional species low. Natural disturbances caused gaps in the forest overstory into which understory white oaks would recruit. This dynamic equilibrium continued for hundreds and thousands of years, leading to the sustained predominance of white oak across the eastern U.S. (Abrams 2003).

1.2 Novel Disturbances Following European Settlement

When European settlers arrived in the eastern U.S., they brought novel land uses that dramatically altered the forest. Fire became more frequent and ubiquitous as settlers cleared land and treated forests as open range to be grazed and burned annually. The growing population of settlers drove land clearing for agriculture and settlements and logging for building materials. These land-use patterns combined with the chestnut blight and unregulated hunting created a novel forest across the eastern U.S. In contrast to the recurring low-intensity disturbances prior to European settlement, the forest disturbances after European settlement could be described as frequent and widespread with low to moderate intensity. Contemporary oak forests regenerated as a result of this period (Dey 2014).

In some regions, the widespread disturbances following European settlement favored red oak and chestnut oak over white oak (Abrams 2003). Land clearing disproportionately affected lower elevation white oak forests versus ridge and mountains forests dominated by chestnut, red oak, and white oak (Abrams 2003). Lower elevations provided better land for agriculture and settlements. Timber harvesting occurred at an unprecedented scale in the eastern U.S. from the 1860s-1920s. The most common harvesting methods during this time were selective harvesting and commercial clearcutting (Dey 2014). The former favored the removal of white oak, the most widely used building material at the time (Abrams 2003); the latter created large-scale clearings in which other fast-growing species sometimes outcompeted white oak. Additionally, timber harvests reduced the white oak seed supply (Abrams 2003).

Ultimately, the novel disturbance regime promoted the regeneration of oak (including white oak) forests across the eastern U.S. While the recurrent, widespread fires allowed for very little oak recruitment of any kind in some regions from about 1850-1930, the advent of fire suppression in the 1930s provided oaks their opportunity (Dey 2014). The novel post-settlement disturbances allowed oaks to persist by creating low-density woodland structures from land clearing for agriculture and settlements, partial canopies from chestnut blight, logging, and burning, and favorable understory conditions of oak regeneration from understory fires that kept densities of less fire-resistant species low. The recurring disturbances allowed oaks to build extensive root systems. When fire suppression began, those oaks recruited into the highly-disturbed overstory (Dey 2014). Concomitantly, the industrial revolution led to the abandonment of marginal agricultural fields (Abrams 2003), and many of the current oak-dominated forests in the eastern U.S. regenerated (Dey and Guyette 2000).

1.3 The Woods They Are A-Changin'

Oaks remain dominant in the overstory of forests across the eastern U.S. However, since the 1950s, foresters have sounded increasingly frequent alarms concerning the sustainability of oak. Since the beginning of the 20th century, the most commonly practiced methods for harvesting hardwoods have been selective cutting (often high grading) that does not follow a formal silvicultural system. By the mid 20th century, it became evident that these methods promoted succession towards shade tolerant species instead of sustaining oak forests (Dey 2014). On intermediate and high-quality sites, small openings in the overstory favor the recruitment of shade tolerant species because fire suppression over the last 90 years has created low light conditions at the forest floor that favor the regeneration and growth of shade tolerant species such as red maple, sugar maple, or birch (Dey and Guyette 2000). Large-scale disturbances and even-aged silviculture, such as clearcutting, favor fast-growing species such as yellow-poplar (Dey et al. 2010).

The inability of oak reproduction to survive and recruit into the overstory is the underlying challenge for sustaining oak (Dey and Guyette 2000). Dey (2014) calls regeneration and recruitment the pillars of oak sustainability. On sites with below-average productivity that undergo recurring fires or droughts, oak regeneration persists. The forest structure created by these conditions favors oak (i.e. limited survival and growth of competing species, and lower overstory density, vertical vegetative structure, and leaf area). Better sites require active management to promote oak regeneration and recruitment (Dey and Guyette 2000). Silviculture provides forest managers and landowners with the tools they need to create repeated disturbances that regulate overstory density, create favorable understory conditions for oak seedlings, and promote the recruitment of oak into the overstory (Dey and Guyette 2000). For example, shelterwood harvests with and without other practices such as prescribed burning has yielded promising results for regenerating oak, and a pre-commercial crop-tree release at the stem exclusion stage can help recruit oak into the overstory (Dey 2014). Still, while the need to actively manage oak forests is clear, foresters are still searching for reliable ways to regenerate, recruit, and sustain oak on a variety of sites across the eastern U.S.

The challenges to oak sustainability extend beyond the widespread increase of late-successional species in the understory of oak-dominated forests. Diseases such as sudden oak death and oak decline threaten the oak resource (Dey 2014; Grunwald et al. 2012). Gypsy moth defoliations can stress oak trees—sometimes leading to mortality (Lovett et al. 2006). The emerald ash borer continues to create small gaps in oak-dominated forests as it wreaks havoc on ash trees (*Fraxinus* spp.) across the eastern U.S., speeding up succession to shade-tolerant species. Up to 300 invasive species have altered the forests in the eastern U.S. in unknown ways (for example, it is unclear if fire will deter or favor the growth and spread of certain invasive species). Widespread herbivory reduces the seed and seedling density of oak (Dey 2014).

In addition to the above biotic impediments, social changes create challenges for the active management of the oak resource. In particular, forest parcelization and diverse landowner goals reduce the silvicultural tools available for forest managers and landowners to effectively promote oak sustainability through active management. Forest parcelization refers to the tendency for large forest holdings with one owner to be divided into smaller forest holdings with multiple owners. Mehmood and Zhang (2001) recognize death, urbanization, income, and regulatory uncertainty as important contributing factor to forest parcelization. The key impact of forest parcelization from an oak management perspective is smaller forestland holdings, which brings a loss of economies of scale for forest owners (Hatcher et al. 2013). Depending on local mills and markets, silvicultural treatments and timber harvests on small forest holdings that promote oak sustainability may not be economically beneficial for forestry professionals. Butler (2008) reports a positive correlation between the size of a forest holding and a landowner having a management plan, receiving management advice, and performing a commercial timber harvest. As parcelization occurs, fewer landowners actively manage their forests—a necessary practice for sustaining oak as it is a disturbance-dependent genus.

The variety of management objectives reported by family forest owners in the U.S. reflect the fact that small forests are rarely actively managed for timber. Across the U.S., 35% of all forestland belongs to family forest owners, of whom 61% own fewer than 10 acres. The top five reasons given by family forest owners for owning forestland are beauty or scenery, leaving to heirs, privacy, protection of nature, and part of home or cabin. Only 10% of family forest owners cite timber production as a reason for owning forestland. Despite this, harvesting timber remains common—54% of family forest owners in the U.S. have performed commercial harvests (Butler 2008). The trends in the eastern U.S. reflect the national trends. In Kentucky, for example, family forest owners own 78% of the state's forestland and give beauty or scenery, leaving to heirs, privacy, nature or biological diversity, and part of home or vacation home as the primary reasons for owning forestland. But 69% of Kentucky family forest owners who do not give timber production as a reason for owning forestland have harvested timber (Kentucky Division of Forestry 2010). Although privately owned forests are rarely actively managed, harvests remain common. Depending on the method, harvesting unmanaged forests will speed up the succession to either shade-tolerant species such as red maple (Abrams and Nowacki 1992) or fast-growing species such as yellow-poplar (Dey and Guyette 2000).

The history of the eastern U.S. forest has been indelibly bound up in human land uses. Consider how Native Americans burning for agriculture, land clearing, or hunting led to a dynamic equilibrium that allowed oak to persist for hundreds and thousands of years; or how European settlers logging, land-clearing, building, and burning led to a major shift in disturbance regimes that allowed the current oak-dominated forests to grow; or how modern-day Americans suppressing fire, dividing their forestland, and passively managing their forests has led to the impending shift from an oak-dominated forest to one dominated by later-successional species. One reasonable response to the current situation is to simply let the existing land uses to continue to shape the forest in the eastern U.S. But this response would reduce the ecologic and economic benefits contributed by oaks—and white oaks, in particular.

From the time of European settlement, white oak has claimed an important place in construction, flooring, and cabinetry in the U.S. In the 1900s, it became the primary wood for the popular mission style furniture (Abrams 2003). Currently in Kentucky, it is the second most valuable hardwood behind black walnut (*Juglans nigra*). The recent demand for white oak barrels, because of the expanding whiskey and wine industries, has driven the value of a white oak stave log in Kentucky up to $1300 per thousand board feet (West 2019). In addition to these economic benefits, white oak provides many ecologic benefits. Acorns provide food for many animals, and a mast year drives ecosystem dynamics. For example, acorn mast years control the long-term dynamics of rodents and songbirds by increasing rodent abundance, which in turn decreases dark-eyed junco (*Junco hyemalis*) abundance (Clotfelter et al. 2007). Oak canopies and leaf litter provide habitat for songbirds, insects, small mammals, and other fauna, and oak ecosystems typically contain high levels of plant diversity and endemism (Dey 2014).

As the forest in the eastern U.S. changes, the people, markets, and species that rely on oak-dominated forests face the possibility of a reduction in the oak resource. Land managers and landowners need to adopt active management using silvicultural practices that promote the regeneration and recruitment of oak and can be applied on small forest holdings and within multifaceted plans. Without this, the reversal of the current trend towards a late-successional forest will be unlikely. Currently, oak-dominated forests are at their peak capacity to produce acorns; however, as the overstory oaks age and shade-tolerant species are recruited into forest canopies, the regeneration potential of oak will continue to dwindle (Dey 2014).

Crop-tree release shows promise as an intermediate treatment for addressing certain challenges in sustaining oak forests. It is a flexible treatment that can be applied to small forestland holdings while promoting the growth and maintenance of overstory oaks through targeted density reduction. The flexibility of crop-tree release makes it appealing in the current milieu on one hand and presents a hurdle in narrowing down its potential on the other hand. The next chapter attempts to overcome this hurdle by synthesizing the current knowledge about crop-tree release.

CHAPTER TWO: LITERATURE REVIEW

2.1 Crop-tree Release

Crop-tree release (CTR) is an intermediate silvicultural treatment in which crop-trees are identified in a stand and then released by removing competing stems in the immediate vicinity. This provides the crop-trees with more favorable conditions—most importantly access to sunlight, but also access to water and soil nutrients. In theory, a crop-tree could be any species over a wide range of ages; many different numbers of crop-trees per acre could be selected; and multiple intensities of release (i.e. one-sided to four-sided crown release) could be employed. CTR studies reflect the wide range of possibilities, but the many common elements among them allow for a holistic assessment of their results which helps define the roles for CTR in forest management and highlights the knowledge gaps where more research would provide clarity.

Trimble (1971) posed six questions crucial to the efficient and effective implementation of CTR:

1. "At what age—or at what stage of stand development—should a crop-tree release be made?"
2. "How many crop-trees per acre should be selected?"
3. "What type of trees should be selected—species, crown class, stem form?"
4. "Who is qualified to select crop-trees?; how should these trees be designated?"
5. "What method should we use to release crop-trees?; how heavy should be the release?"
6. "What can we expect this operation to cost?"

These questions provide an excellent framework for a discussion of CTR, and with the exception of questions 4 (which focuses on the operational aspects of CTR) they will be discussed below.

1. *"At what age—or at what stage of stand development—should a crop-tree release be made?"*

The age at which CTR is effective varies widely. Many studies have used stands under 25 years in age (Kenefic et al. 2014; Lamson 1989; Lamson and Smith 1978; Lamson et al. 1990; McNab 2010; Miller 1984, 2000; Sendak 2008; Smith 1983; Sonderman 1987;

Trimble 1971, 1974; Ward 2013, 2017), while fewer studies have used stands old enough for small sawtimber (Demchik et al. 2018; Lamson et al. 1990; Smith et al. 1994; Ward 2002, 2007). Typically, when these studies evaluate the growth of diameter at breast height (breast height = 4.5', dbh from now on), the increase of dbh is significantly greater with CTR than without it. Most studies, with the exception of Sonderman (1987), in which young released yellow-poplar (*Liriodendron tulipifera*) crop-trees exhibited a greater height increase than those unreleased, show that CTR does not significantly increase the height growth of crop-trees. Some studies have even found height growth to be significantly lower with CTR than without it (Lamson 1989; Miller 2000). All of the studies that take a particular interest in changes in height involve stands under 25 years in age. CTR at this stage in stand development often incorporates both the goal of dbh increase and the goal of maintaining a competitive height in order to promote crop-tree survival and dominance as well as influence the species composition of the stand. In studies conducted in stands with small sawtimber-sized trees, height growth becomes less important as crop-trees benefit most from increased dbh growth. However, in stands under 25 years in age, CTR effects on height growth can be important, and studies evaluating the persistence of crop-trees in upper canopy positions have found varying results. Lamson and Smith (1978) and Trimble (1973) found CTR in young stands resulted in crown class regression, while Ward (2013) reported an increase in upper canopy persistence. Taking into consideration the varying goals of CTR based on stand age, several guidelines regarding when to apply CTR emerge from these studies. CTR produces positive results for dbh growth and crown class maintenance as early as 17 to 23 years (Sonderman 1987; Ward 2013) or at a height of 15 to 25 ft (Smith 1983; Trimble 1973). Ward (2008) offers at least 90 years as an upper limit for CTR.

2. *"How many crop-trees per acre should be selected?"*

The number of crop-trees per acre can vary widely based upon stand age, site characteristics, management objectives, and species. Stand age often determines the number of potential crop-trees available to be released, as stem number decreases as stand age increases. Trimble (1971) released 109 crop-trees per acre in a stand aged 7-9 years old. In contrast, Smith et al. (1994), using two treatment levels in a 65-year-old stand, released 40 crop-trees per acre and 60 crop-trees per acre. In managed white oak stands, Stringer et al. (1988) estimated that 22 crop-trees with a 24-inch dbh would occupy 80% of the growing space in an acre (Stringer et al. 1988). Given this estimation, selecting and releasing 109 crop-trees per acre could result in shouldering higher treatment costs than necessary. Following this line of thought, Smith (1983) recommends releasing no more than 50-75 crop-trees per acre in a 10 to 12-year-old stand in order to reduce treatment cost. On the other hand, selecting more crop-trees than will survive through the end of the rotation provides for uncertainties and mortalities while potentially increasing the revenue available at the first commercial thinning. Additionally, CTR accommodates objectives outside of timber management, and the considerations above become less important within other objectives (e.g. promoting seed sources or preserving specific trees). CTR studies and their recommendations indicate the importance of considering management objectives and stand development patterns when choosing the number of crop-trees to release.

3. *"What type of trees should be selected—species, crown class, stem form?"*

A general agreement about the criteria of a crop-tree exists across the majority of CTR studies, which generally focus on timber management. Other management objectives might require a different set of criteria. As with stand age and crop-tree number, CTR studies include a variety of both species and qualifications of crop-trees. Although some studies (Kenefic et al. 2014) have selected softwood crop-trees, most studies concern hardwood crop-trees. Location and markets drive species selection. For example, while Sendak (2008) studies paper birch (*Betula papyrifera*), yellow birch (*Betula alleghaniensis*), sugar maple (*Acer saccharum*), and white ash (*Fraxinus americana*) in New Hampshire, Smith et al. (1994) study black cherry (*Prunus serotina*) and maple (*Acer* spp.) in West Virginia. A significant number of studies look at red oak (*Quercus* spp.) (Demchik et al. 2018; Kenefic et al. 2014; Lamson and Smith 1978; Lamson et al. 1990; McNab 2010; Miller 2000; Morrissey et al. 2011; Schuler 2006; Sonderman 1987; Ward 2002, 2007, 2008, 2013). Studies on white oak are conspicuously absent (except for in the case of a simulation (Morrissey et al. 2011)). As white oak ranks among the most valuable and abundant oaks in the eastern U.S. (Abrams 2003), it deserves attention. While the diversity among studies in crop-tree criteria matches the diversity of species selected for CTR, the generally-agreed-upon crop-tree qualifications for a timber objective include: dominant or codominant crown class, potential USFS tree grade 1 or 2, and characteristics that indicate vigor. While studies differ in the details they consider (for example, 17 feet to the first fork (Ward 2002), no evidence of insect or disease (Lamson 1989), or no broken crown (Miller 2000)), they share the general qualifications listed above.

5. *"What method should we use to release crop-trees?; how heavy should be the release?"*

In order to maximize diameter growth and facilitate persistence in the upper canopy, studies highlight the importance of an adequate crown-touching release. The majority of CTR studies have focused on four-sided release (Ward 2002, 2008), showing positive results. In studies that explicitly evaluate the effectiveness of different levels of release (Lamson et al. 1990, Smith et al. 1994, Ward 2007), a three or four-sided crown-touching release provided a significant growth advantage compared to releasing 1 or 2 sides for the oak species studied. Lamson et al. (1990) also found a species effect, noting that yellow-poplar maintained a linear response to number of sides released, whereas select oak species did not show an increase in dbh growth between a 3 and 4 side release. All of these studies point to the necessity of sufficient release to yield significant growth responses. However, one risk in CTR is the development of epicormic branching in the butt-log of crop-trees, which could lead to a reduction in timber value. Epicormic branching refers to branches that arise from dormant buds, often following exposure to higher light levels. While Smith et al. (1994) does not observe this, in some cases crop-trees develop a significant number of epicormic branches (Ward 2002). Sonderman (1987) observes that oak crop-trees, in particular, develop epicormic branches after release. Crop-trees typically do best in terms of dbh growth with a significant release, but the potential decrease in butt-log value needs more research.

6. "*What can we expect this operation to cost?*"

The financial aspect of CTR needs more research. In a simulation of the long-term financial benefits of CTR, Demchik et al. (2018) report that the Internal Rate of Return (IRR), the rate of return at which the net present value (NPV) equals 0 (Laws 2018), decreases as crop-trees increase in size, but that the IRR increases as more sides of a crop-tree are released. Based on the assumption that crop-trees have grade 1 or veneer logs, the IRR dropped below 4% (the acceptable rate of return in the study) when crop-trees reached the 18-inch dbh class. If crop-trees are sold as grade 2, bolt, or pulpwood, the IRR dropped to 4% at the 14-inch dbh class (Demchik et al. 2018). This highlights the role of product in the economics of CTR. In another simulation, CTR increased NPV of 20-30-year-old stands by $245-492, while also increasing the proportion of hard-mast species in the stand—an indirect use value (Morrisey et al. 2011). In contrast, Sendak (2008) finds that 45 years after a CTR application in a 24-year-old stand, no significant financial improvement occurs. Once again, stand age can alter the effectiveness of CTR. As Trimble (1973) notes, when interest rates are considered, cultural work done in a young stand becomes expensive. In contrast, a commercial release, depending on local markets, could provide financial benefits now and in the future. The role stand age, product, and indirect use value play in the cost of CTR remains unclear, and the financial benefits of CTR needs more thorough evaluation in general.

2.2 Study Objectives

Multiple studies evaluate the response of red oak to CTR, but the number of studies that explore the effectiveness of CTR for white oak are sparse in comparison. Bearing in mind its slower growth relative to red oak (Gingrich 1967) and its predisposition for epicormic branching following thinning (Dale 1968), we should not assume that white oak responds to CTR exactly like red oak. The CTR literature recommends a three to four-sided release, but warns that too much light might promote epicormic branching that reduces the butt-log value of the crop-tree. Some studies have noted an increase in defects per square foot after CTR (Sonderman 1987), but we do not know if these defects contribute to a significant loss of quality that results in a less valuable crop-tree. The first objective of this study addresses these questions by examining the effects of CTR on the growth and quality of small sawtimber-sized white oak crop-trees over 35 years. Many studies have addressed the effects of CTR on crop-trees, but Ward (2009) also reports that accidental release from CTR promotes growth for non-crop-trees. The second objective of this study expands the tree-focused perspective of CTR to a stand-level perspective by evaluating how CTR alters stand structure as well as per-acre value.

CHAPTER THREE: METHODOLOGY

3.1 Project Location

Robinson Forest is a 14,800-acre research forest covering parts of Breathitt, Perry, and Knott counties in Southeastern Kentucky. In 1923, after logging its virgin timber, E.O. Robinson conveyed the forest in trust to the University of Kentucky for the purposes of research, teaching, and reforestation (Robinson Forest). Robinson Forest is within the Northern Cumberland Plateau ecological section of the United States (Cleland et al., 2007). The climate of the region is humid subtropical having an average daily temperature of 1.6–9.1°C in November through March and 14.1–24.1°C in April through October. Annual precipitation averages 122.8 cm.

3.2 Field Methods: Stand Selection and Description

In 1983, twelve 2-acre white oak dominated stands were selected for study. The stands occurred on Southern aspects towards the bottoms of slopes and stretching 200-300 feet upslope (Stringer et al. 1988). At the time of selection, they were 70-80 years old with an average site index of 73.5 and an average basal area of 111 square feet, of which white oak comprised 58%.

3.3 Field Methods: Crop-tree Selection and Release

A tree needed to meet five criteria in order to be selected as a crop-tree:

1. Dominant or codominant crown class;
2. White oak species;
3. Potential USFS tree grade 1 or 2;
4. Even spacing with other crop-trees in the stand;
5. All things equal, trees with larger dbh (diameter at breast height).

Each crop-tree received a four-sided crown-touching release, in which any tree in the same canopy class as the crop-tree that touched the crop-tree's canopy as well as any intermediate crown class tree that would directly compete with the crop-tree after release were removed using a chainsaw. In cases where crop-trees neighbored one another, each crop-tree received a three-sided release (Stringer et al. 1988).

Three treatment levels were applied to the twelve stands. The treatment levels were developed according to three assumptions: first, a crop-tree can grow up to 0.3" dbh per year; second, the initial average crop-tree size is 13" dbh; and finally, the average crop-tree size at the end of the rotation will be 24-26" dbh. Given these assumptions, in thirty-five years, 34 crop-trees averaging 24" dbh in size would occupy 80% of the available growing space in an acre. More than 34 crop-trees per acre would not promote the growth of the crop-trees through the end of the rotation. For these reasons, in addition to a Control level in which crop-trees were selected but not released, 34 crop-trees per acre and— arbitrarily— 20 crop-trees per acre were selected as the treatment levels. The twelve plots were grouped according to site index, which differed significantly among plots, and randomly assigned a treatment, resulting in four replications of the three treatments levels (Stringer et al. 1988). While grouping by site index allowed treatments with similar site qualities, the treatments varied in age. By chance, the Control treatment, which was 82.75±6.02 years, was older on average. The 20 CTR and 34 CTR treatments were more similar in age (70.75±3.57 years and 67±6.45 years, respectively).

3.4 Field Methods: Half-acre Measurement Plot

A 0.5-acre measurement plot was established within each 2-acre stand, giving the measurement plot an approximately 75 ft. treatment buffer from the surrounding untreated forest. The four corners of each 0.5-acre measurement plot were delineated with rebar and within this boundary all trees ≥1” dbh were measured and tagged with a unique ID number. The method used to tag each tree involved installing a length of #9 galvanized wire into the base of a tree 1 meter below dbh and then affixing a brass tag stamped with a unique identifying number to the wire. In 1983, 1989, 1993, 2001, and 2019 all tagged trees were measured. New (in-growth) trees recruited into the ≥1” dbh size class were tagged and measured in 1989, 1993 and 2001. In 2019, all trees recruited into the ≥1” dbh size class were measured but not tagged. Instead, each tree was assigned a unique ID during analysis according to the order in which it appeared in the field datasheets. Measurements in all years included species, dbh, crown class (dominant, co-dominant, intermediate, or overtopped), number of stems, and mortality, and for crop-trees, USFS tree grade.

The measurements taken in 2019 included the following additions: USFS tree grade for a subsample of non-crop-trees and a more detailed timber quality evaluation of all graded trees. To determine representative subsamples of non-crop-trees, the qualifying trees in each plot (i.e. non-crop-trees ≥9.6” dbh) were sorted into three diameter classes and six market-derived species groups: white oak, red oak, hickory, beech, magnolia, and other. The diameter classes reflect the USFS tree grading criteria: 9.6-12.6” dbh, >12.6-15.6” dbh, and >15.6” dbh. After sorting the qualifying trees, a frequency value, which represents the frequency with which a type of tree appears in the ½-acre measurement plot, was calculated by plot for each specific type of tree (e.g. a hickory in the >12.6-15.6” dbh diameter class in Plot 8 has a frequency value of 0.08). This frequency value was then multiplied by 15, the desired subsample size, and rounded to a whole number to find the number of trees of a specific type needed for a representative subsample. The desired subsample size was based on the goal of sampling ~50% of the qualifying trees in a plot. Plots 1 and 12 contained 30 and 32 qualifying trees, respectfully; all other plots contain fewer qualifying trees. A subsample of 15 trees allows for nearly half or more of the qualifying trees in any given plot to be graded. Finally, using the R programming language (R Core Team 2020), tree ID numbers of qualifying trees were randomly selected within a diameter class and species group for all plots. Exceptions to the method described above include: if only 1 representative of a diameter class and species group existed, it was included in the subsample; if a plot contained fewer than 15 qualifying trees, all qualifying trees were included in its subsample; and, because the process of determining a subsample suggested 17 trees in Plot 5, which only contained 18 qualifying trees, all qualifying trees were included in the subsample for Plot 5.

Both the crop-trees and the subsample of non-crop-trees were graded using the USFS hardwood tree grading standards Hanks (1976). USFS tree grade is based on dbh, the diameter inside top, defect indicator free area, and cull deduction of a 12, 14, or 16-foot section (grading section) of the second worse face (grading face) of the 16-foot butt-log. In addition to the USFS tree grade, crop-trees and the subsample of non-crop-trees were assigned a product type aligning with higher valued log products. This product type provides a more nuanced evaluation of tree quality and value than possible from the USFS tree grade alone. Because the USFS tree grading system is designed for factory lumber logs, it does not differentiate trees that can be used for products such as veneer, or in the case of white oak, stave logs. These products are valued at a much higher value than lumber logs, making the product type an important distinction to make.

Because no detailed standards exist for grading veneer and stave logs, we developed a measure that reflects the range of quality typically encompassed by veneer and stave logs. In order to develop this measure, we evaluated procurement standards obtained from four cooperages, which purchase over 70 percent of the stave logs regionally, and three major veneer producers. The measure encompasses the standards necessary for these high-value products, is repeatable, and represents a conservative approach to product classification. The product type classifications include:

- Veneer: a USFS tree grade 1 tree having at a minimum four faces that were defect indicator free over a 12-foot section,
- Stave 1: a USFS tree grade 1 or 2 tree having three 12-foot defect indicator free faces,
- Stave 2: a USFS tree grade 1 or 2 tree having two defect indicator free 12 ft faces.

The classification titles generally reflected the product potential of the 16-foot butt-log.

3.5 Statistical Methods: Crop-tree Variables

We analyzed two dbh variables to examine the treatment effects on crop-tree growth: average crop-tree diameter (avg. dbh) and periodic annual diameter increment (PAI dbh), both expressed in inches. We calculated the avg. dbh at the plot level by finding the mean dbh at each measurement for crop-trees which survived over the duration of the study. We first calculated the PAI dbh at the crop-tree level and then expressed it at the plot level as a mean. The PAI dbh refers to an annualized growth metric determined by taking the difference between the dbh of a crop-tree at two consecutive measurements and dividing it by the number of years between measurements (ex. 13.85 inches dbh in 1983 (year 0) and 14.82 inches dbh in 1989 (year 5) yielding a difference of 0.97 inches was divided by 5 (the number of growing years between 1983 and 1989) to determine a PAI dbh of 0.19 inches).

To determine the effect of treatment on crop-tree quality, we tested the proportion of crop-trees reaching their maximum potential grade (MaxPG). The MaxPG of a crop-tree denotes the tree grade for which a specific crop-tree qualifies based on its dbh. For example, a crop-tree over 15.6 inches in dbh has a MaxPG of grade 1. We determined the proportion of crop-trees reaching their MaxPG by creating a binary variable in which 1 indicated the crop-tree reached its MaxPG and 0 indicated it failed to reach its MaxPG. We then counted this binary variable to create plot-level summaries at each measurement year with a success variable, the number of 1's in a plot, and a failure variable, the number of 0's in a plot. We used these the success and failure variables in the binomial test described below in section 3.7 "Statistical Methods: Analyses."

This method of evaluating crop-tree quality reduces the confusion caused by varying dbh measurements among crop-trees. The proportion of MaxPG allows a crop-tree in the dbh class 9.6-12.6 to be compared to a crop-tree in the dbh class >15.6 as either crop-tree could fail to achieve their MaxPG but only one meets the minimum qualification to be a grade 1 tree. For this reason, the proportion of the MaxPG became the crux of the quality analysis; nevertheless, we calculated grade distributions, expressed as the average percentage of crop-trees in each grade at the treatment level, and product distributions, also expressed by treatment as the average percentage of crop-trees in a product category. Due to the inherent limitations in interpreting statistical tests of the grade and product distributions as described above, they were not tested.

We computed the crop-tree butt-log value in 2019 using the stumpage price for the product category for which the crop-tree qualified and the board foot volume of the 16-foot butt-log of the crop-tree in 2019. The stumpage price for each product category was derived from the statewide delivered log prices from the 3rd and 4th quarters in 2019, collected from mills throughout Kentucky and reported by West (2019). This report includes high and low values for each product type. The Stave 1 value was the average high value for reported stave log prices, and the Stave 2 value was the average of the high and low values for reported stave log prices. Veneer value was the average high value for reported veneer white oak log prices for two reasons: the low veneer value overlapped with stave prices, and lower valued veneer logs were being purchased for higher valued stave logs in 2019. Grade 1, 2, and 3 values were taken from the high, medium, and low, values for delivered log prices. Stumpage values were 50 percent of delivered log values, a statewide representative pricing differential. Stumpage price refers to the value of the product prior to harvesting, based on the delivered mill value minus the harvesting and transportation costs as well as the harvesting profits. Typically, stumpage prices are 40-60% of the delivered log prices (Dr. Jeffrey Stringer, personal communication).

After determining the stumpage price for each product category, we calculated the board-foot volume of each crop-tree butt-log following Wiant (1986) and using appropriate coefficients for the Doyle log rule. Next, we estimated the mean crop-tree butt-log value by multiplying the butt-log volume by the stumpage price and dividing by 1,000 to convert the stumpage price from $/MBF to $/board feet. These values were averaged by plot to determine the mean per-crop-tree butt-log value in 2019 by plot.

3.6 Statistical Methods: Stand Level Variables

In order to determine the stand-level response to CTR, we calculated the total basal area (BA) per acre and percent stocking. BA was calculated by multiplying the constant 0.005454 by the dbh of a tree, and then multiplying the result by the plot size expansion factor (i.e. 2 trees per acre) to express the BA of a tree in ft$_2$/acre. Next, the BA of all the trees in a plot were summed to find the BA ft$_2$/acre by plot. Percent stocking was determined at the plot level using dbh and trees per acre, following Gingrich (1967). In addition to total percent stocking, we calculated the percent stocking by tree classification (crop-tree, non-crop-tree, ingrowth) and crown position (upper, intermediate, understory).

Finally, we calculated the average total ingrowth in trees per acre in each treatment as well as the percentage of ingrowth by species in each treatment. Ingrowth refers to all trees persisting through 2019 that grew into the ≥1-inch dbh class after 1983.

We calculated the net present value (NPV) per acre at the stand level using the 2019 butt-log value of the crop-trees, non-crop-trees, and removed trees. We calculated the 2019 butt-log value of a tree by multiplying 2019 stumpage prices ($/MBF) by the board-foot volume (Doyle log rule) of the tree and dividing by 1,000 to express it in $/board feet. For the crop-trees, the butt-log value of each tree was multiplied by 2 in order to express it on a per-acre basis and summed by plot. For the non-crop-trees, we calculated the average butt-log value of the subsample non-crop-trees in a particular diameter class and species group (see "Field Methods: Half-acre Measurement Plot"), determined the total number of non-crop-trees per acre by species group and diameter class in each plot, multiplied the average butt-log value by the non-crop-trees per acre within each species group and diameter, and summed them by plot. Based on the assumption that the value of a removed tree in a certain species group and diameter class in 1983 would be the similar to the average value of a tree in the same species group and diameter class in 2019, we estimated the per-acre butt-log value of removed trees in the same manner as non-crop-trees. By using 2019 stumpage prices, we expressed the value of the removed trees in 2019 terms. Finally, we found the plot-level NPV per acre by summing the three values.

3.7 Statistical Methods: Analyses

For the crop-tree variables avg. dbh and PAI dbh as well as the stand-level variables BA and percent stocking, we performed a repeated-measures analysis of variance (ANOVA). We created the linear model for each variable with the "lm" function from the "stats" package in R (R Core Team 2020). The model included the main effects of treatment and year (or period for the PAI variables) as well as the interaction effect between treatment and year (or period). Effects were tested for using the "Anova" function from the "car" package with "type" specified as a Type III ANOVA (Fox and Weisberg 2011). Pairwise comparisons using Tukey's HSD were performed using the "emmeans" and "contrast" functions from the "emmeans" package (Lenth 2018). For the crop-tree butt-log value and stand butt-log value in 2019, we performed a one-way ANOVA following the same method we applied for the repeated measures ANOVA. The linear model for the one-way ANOVA excluded the year variable.

We tested for treatment effects on the proportion of crop-trees reaching their MaxPG with a binomial model to represent the nature of this dependent variable. Using the "glm" function from the "stats" package in R and specifying "family" as "binomial", we created a generalized linear model which uses the failure variable and success variable as the response and the main effects of treatment and year as well as the interaction effect between treatment and year (R Core Team 2020). The effects were tested with a Type III ANOVA with the "Anova" function from the "car" package (Fox and Weisberg 2011). Pairwise comparisons were performed using Tukey's HSD post-hoc test and the "emmeans" and "contrast" functions in the "emmeans" package (Lenth 2018). Results were evaluated at a 0.05 significance level.

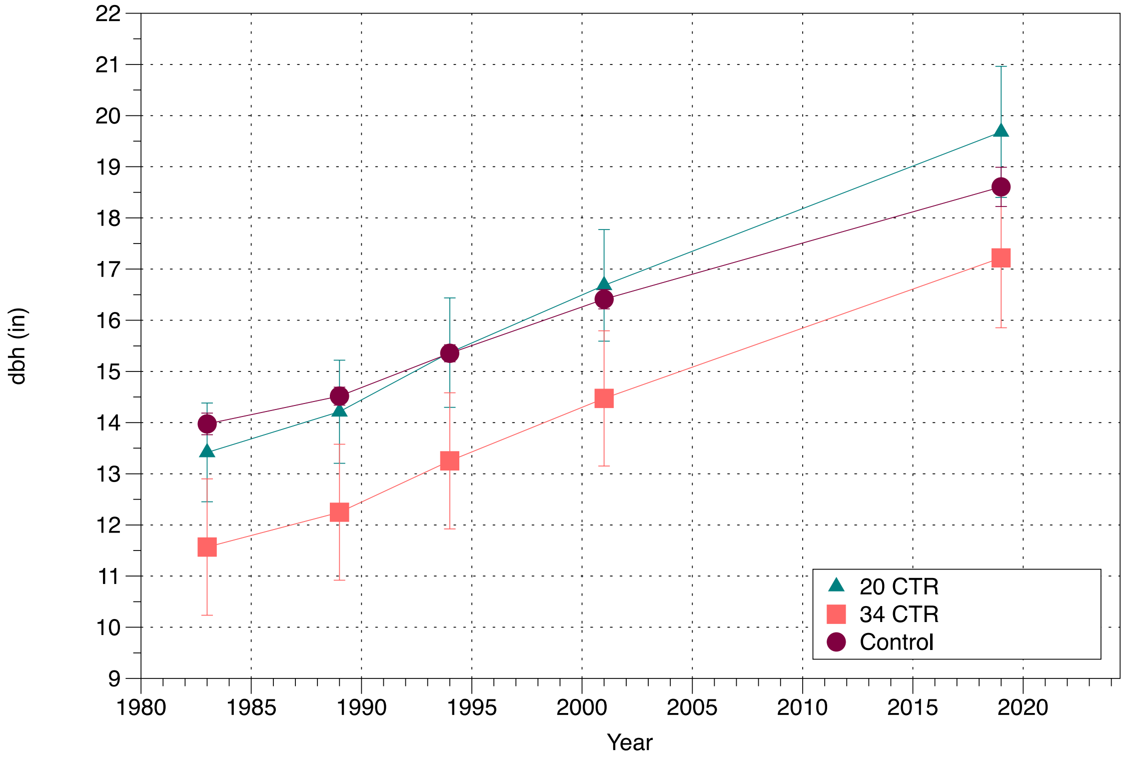
CHAPTER FOUR: RESULTS

4.1 Crop-tree Diameter Growth

At the outset of the study, the crop-trees in the 34 CTR treatment and the 20 CTR treatment averaged 11.59 ± 2.79 inches and 13.11 ± 1.5 inches in dbh, respectively. By chance, crop-trees in the Control treatment were larger in 1983 averaging 14.14 ± 0.67

inches in dbh. By 2019, the average crop-tree in the 20 CTR treatment grew to 19.61 ± 2.48 inches dbh, a 6.5 inches change, while the average crop-tree in the Control treatment only grew 4.51 inches to 18.61 ± 0.77 inches dbh, and the average crop-tree in the 34 CTR treatment grew 5.63 inches to 17.22 ± 2.73 inches dbh (Figure 1).

Figure 1. Average Crop-tree Diameter Over Time by Treatment



(Figure 1: The average dbh (inches) of crop-trees over time (year) by treatment.)

The ANOVA test for the avg. dbh of the crop-trees showed no interaction effect, but both main effects of treatment [$F(2, 45) = 7.10$, $P < 0.01$] and year [$F(4, 45) = 14.04$, $P < 0.001$] were significant. When compared to the 20 CTR treatment and the Control treatment, the 34 CTR treatment contained crop-trees with a smaller average dbh (Table 1). The avg. dbh of crop-trees across treatments was not significantly larger between consecutive measurements. Intervals of 17 or more years led to crop-trees with significantly larger avg. dbh (Table 2).

Table 1. Average Crop-tree Dbh by Treatment

Treatment	Mean dbh	Standard Error
	……………………………(in)……………………………	
20 CTR	15.87_{a}	0.66
34 CTR	13.75_{b}	0.70
Control	15.77_{a}	0.39

(Table 1: The average dbh (inches) of crop-trees by treatment. Shared subscripts (a, b) denote no significant difference, while differing subscripts indicate a statistical difference.)

Table 2. Average Crop-tree Dbh by Year

Year	Mean dbh	Standard Error
	……………………………(in)……………………………	
1983	12.99_{a}	0.59
1989	13.66_{ab}	0.59
1994	14.66_{ab}	0.60
2001	15.85_{b}	0.60
2019	18.50_{c}	0.65

(Table 2: The average dbh (inches) of crop-trees by year. Shared subscripts (a, b, c) denote no significant difference, while differing subscripts indicate a statistical difference.)

The PAI dbh of crop-trees differed significantly by treatment [$F(2, 36) = 14.40$, $P < 0.001$] and period [$F(3, 36) = 14.79$, $P < 0.001$]. Crop-trees in the 20 CTR treatment and 34 CTR treatment grew at similar rates, both significantly greater than unreleased crop-trees

(Table 3). Across treatments, the crop-trees grew at a lower rate from 1983-1989 than from 1989-1994 and 1994-2001. The rate of diameter growth in 1989-1994 was also higher than in 1994-2001 (Table 4). The interaction effect was not significant for PAI dbh.

Table 3. Average Periodic Annual Dbh Increment of Crop-trees by Treatment

Treatment	Mean PAI dbh	Standard Error
	……………………………(in)……………………………	
20 CTR	0.19_a	0.010
34 CTR	0.17_a	0.007
Control	0.14_b	0.009

(Table 3: The average PAI dbh (inches) of crop-trees by treatment. Shared subscripts (a, b) denote no significant difference, while differing subscripts indicate a statistical difference.)

Table 4. Average Periodic Annual Dbh Increment of Crop-trees by Period

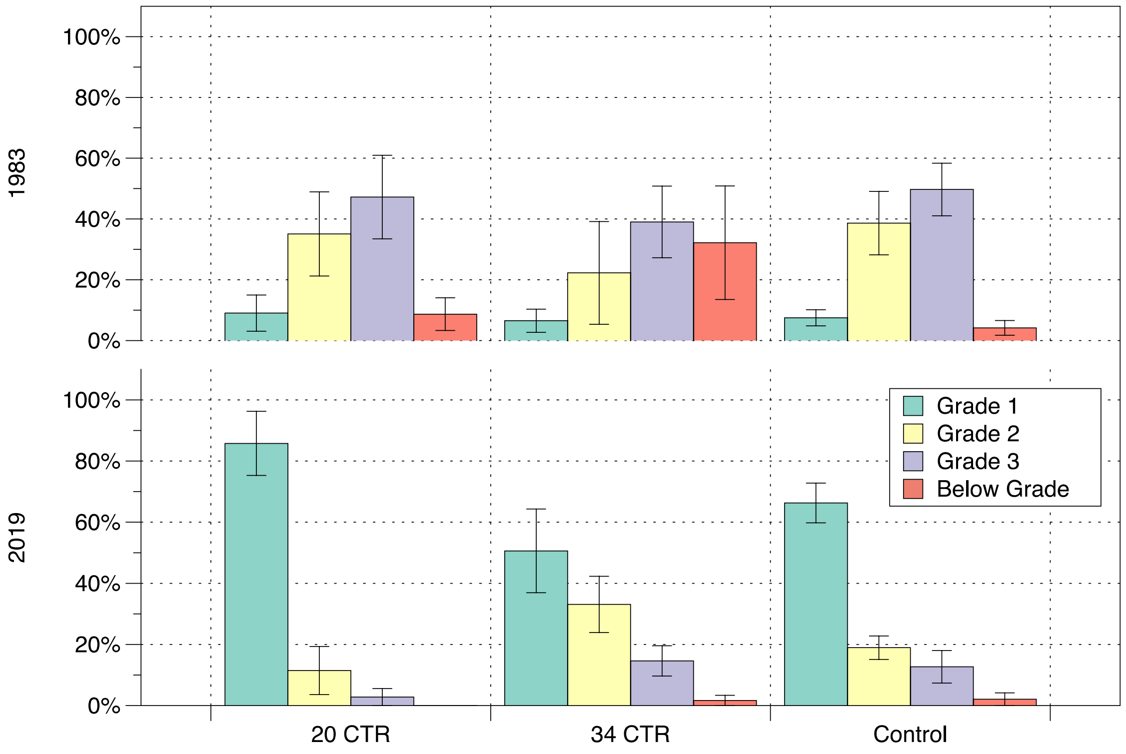
Period	Mean PAI dbh	Standard Error
	……………………………(in)……………………………	
1983 to 1989	0.13_a	0.008
1989 to 1994	0.20_b	0.012
1994 to 2001	0.17_c	0.007
2001 to 2019	0.15_{ac}	0.008

(Table 4: The average PAI dbh (inches) of crop-trees by period. Shared subscripts (a, b, c) denote no statistical difference; differing subscripts denote statistical difference.)

4.2 Crop-tree Quality

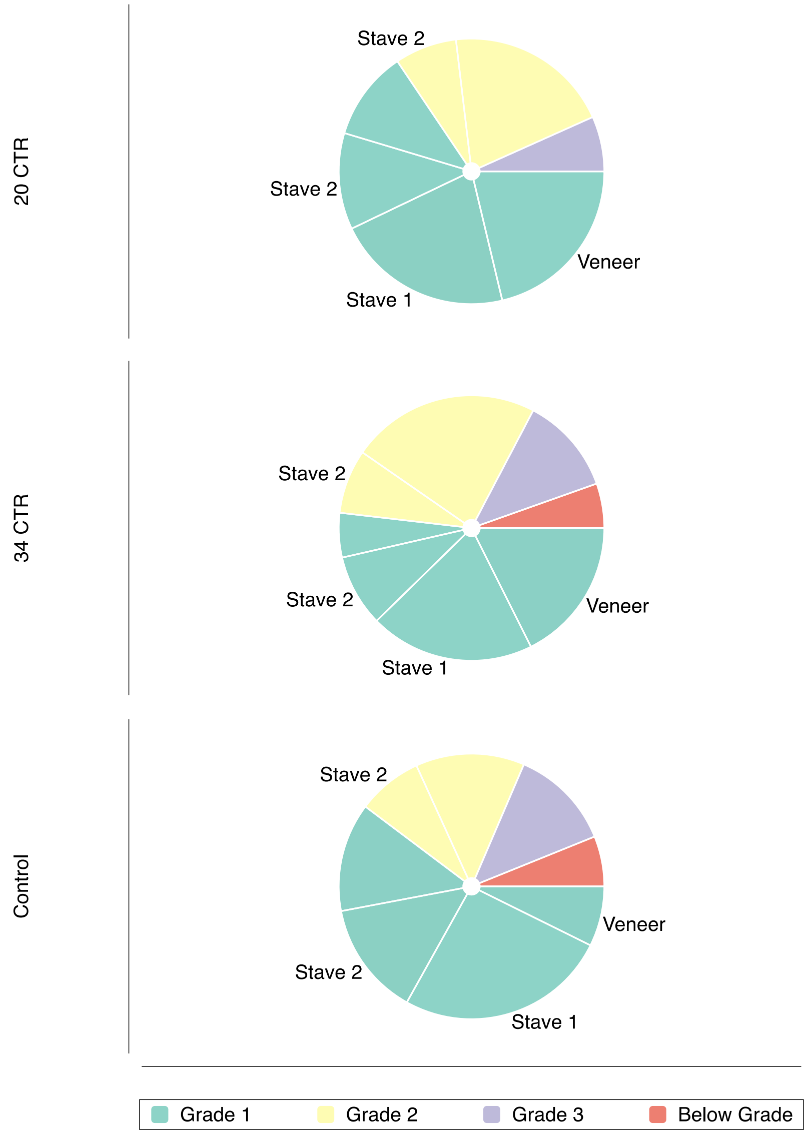
In 1983, grade 1 crop-trees were uncommon and grade 3 crop-trees were most common across all treatments. The 34 CTR treatment contained a relatively large percentage of below grade crop-trees, likely due to the small size of many crop-trees in this treatment. By 2019, below grade crop-trees were uncommon in the 34 CTR treatment and Control treatment, and entirely absent in the 20 CTR treatment. Grade 1 dominated the 20 CTR treatment and the Control treatment, accounting for 86% and 66% of the crop-trees, respectively, and accounted for just over half of the crop-trees in the 34 CTR treatment (Figure 2). The released treatments contained more Veneer trees on average than the Control treatment in 2019. Stave 1 and Stave 2 trees were distributed similarly across treatments (Figure 3).

Figure 2. Crop-tree Grade Distribution in 1983 and 2019 by Treatment



(Figure 2: Percentage of crop-trees in grades 1, 2, or 3, or below grade at 1983 and at 2019 by treatment.)

Figure 3. Crop-tree Product Distribution in 2019 by Treatment



(Figure 3: Percentage of crop-trees in each grade and product category in 2019 by treatment. Grade 1 trees could be assigned a Veneer, Stave 1, or Stave 2 product type, and grade 2 trees could be assigned a Stave 2 product type. The legend denotes the colors that correspond with each grade, and the labels denote the slices that represent the product type within each grade. Slices without labels include trees within a grade that did not qualify for a distinct product type.)

The proportion of crop-trees which reached their MaxPG differed by treatment ($\chi_2 = 34.07$, $P < 0.001$) and by year ($\chi_2 = 25.39$, $P < 0.001$); however, no interaction effect was indicated by the ANOVA. The likelihood that crop-trees in the 20 and 34 CTR treatments would reach their maximum grade was similar, and released crop-trees were more likely to achieve their MaxPG than unreleased crop-trees (Table 5). Across treatments, the proportion of crop-trees reaching their MaxPG was greater in 2019 than in 1994 and 1989 (Table 6).

Table 5. Average Proportion of Crop-trees Reaching Their MaxPG by Treatment

Treatment	Mean	Standard Error
	……………………………(%)……	……………………………
20 CTR	76.53_a	4.29
34 CTR	78.09_a	2.25
Control	55.17_b	3.26

(Table 5: Average proportion expressed as a percentage (%) of crop-trees reaching their maximum potential grade (MaxPG) by treatment. Shared subscripts (a, b) indicate no statistically significant difference; differing subscripts indicate statistically significant difference.)

Table 6. Average Proportion of Crop-Trees Reaching Their MaxPG by Year

Year	Mean	Standard Error
	……………………………(%)……………………………	
1983	73.73_{abc}	5.01
1989	59.02_{bc}	4.23
1994	61.99_{bc}	5.46
2001	73.36_{abc}	4.64
2019	81.54_{a}	4.72

(Table 6: Average proportion of crop-trees reaching their maximum potential grade (MaxPG) by year. Shared subscripts (a, b, c) denote lack of statistical significance; differing subscripts indicate statistically significant differences.)

4.3 Crop-tree Value

In 2019, the average butt-log value per crop-tree in the 20 CTR treatment trended higher at $154.63, while values in the Control and 34 CTR treatments were $89.32 and $84.32, respectively (Table 7). However, average butt-log value per crop-tree was not statistically different among treatments [$F(2, 9) = 1.38$, $P = 0.3$].

Table 7. Average Butt-Log Value Per Crop-tree in 2019 by Treatment

Treatment	Mean Value	Standard Error
	……………………………(USD)……………………………	
20 CTR	154.63	47.28
34 CTR	84.12	28.95
Control	89.32	6.37

(Table 7: Average value (USD) per crop-tree in 2019 by treatment. Mean value refers to value calculated using total predicted height. Mean Butt-log Value is the value calculated using the 16-foot butt-log.)

4.4 Stand NPV

The NPV did not vary significantly among treatments. The 20 CTR treatment generated a marginally higher NPV at $3817.22, followed by the 34 CTR treatment at $3570.23, and finally the Control treatment at $3499.74 (Table 8).

Table 8. Average NPV by Treatment

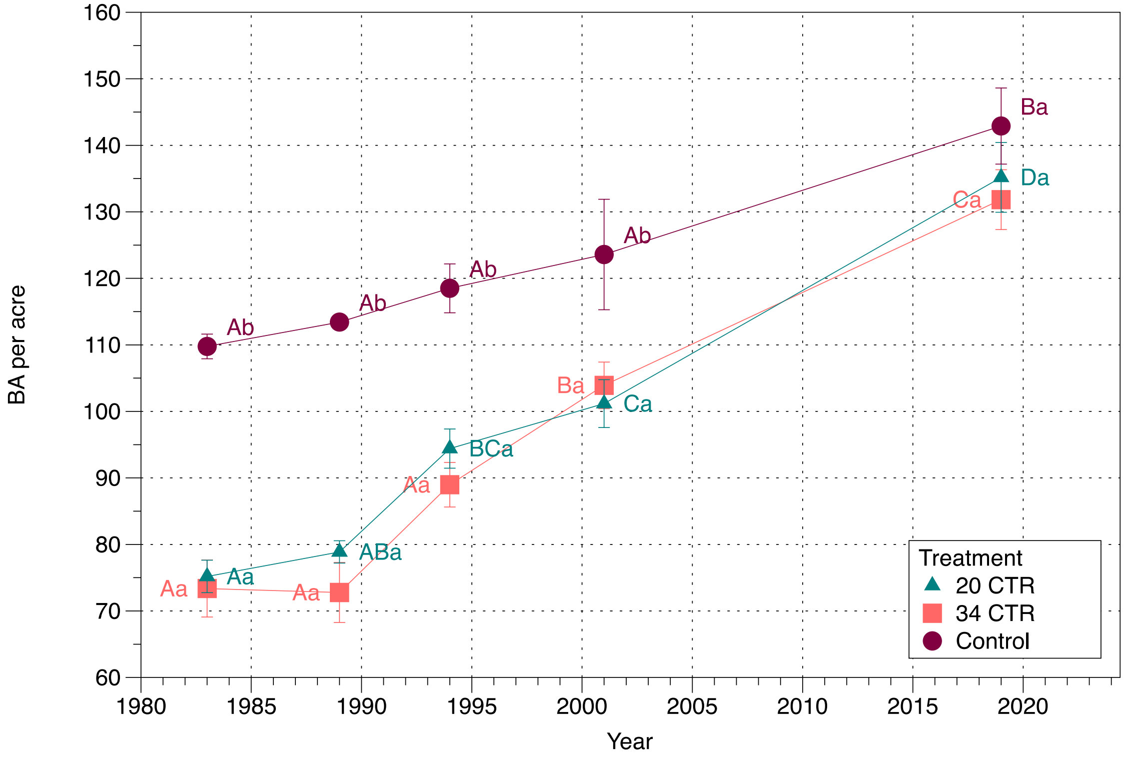
Treatment	Mean NPV	Standard Error
	……………………………(USD)……………………………	
20 CTR	3817.22	976.25
34 CTR	3570.23	661.17
Control	3499.74	475.98

(Table 8: Average NPV (USD) at the stand level in 2019 by treatment.)

4.5 Stand Basal Area Per Acre

An interaction effect between treatment and year showed statistical significance for BA per acre [$F(8, 45) = 2.85$, $P = 0.01$]. Pairwise comparisons revealed that the 20 and 34 CTR treatments contained a significantly lower average BA per acre than the Control treatment in every measurement year until 2019 (Figure 4). For the 20 CTR treatment, the average BA per acre increased significantly among measurements separated by intervals of 10 or more years. The 34 CT treatment had identical results, except that the average BA per acre in 1994 was not significantly larger than in 1983. The BA per acre was only larger than previous measurements in 2019 for the Control treatment (Figure 4).

Figure 4. Average Basal Area Per Acre Over Time



(Figure 4: Average Basal Area (BA) per acre over time (year) by treatment; lowercase letters indicate differences between treatments by year and uppercase letters indicate differences between years by treatment. The letters corresponding to the 20 CTR treatment appear immediately to the right of the triangle, and those corresponding to the 34 CTR treatment appear immediately to left of the square.)

4.6 Stand Percent Stocking

Percent stocking differed across treatments [$F(2, 45) = 26.04$, $P < 0.001$] and across years [$F(4, 45) = 41.19$, $P < 0.001$]; however, no interaction effect occurred. The 20 and 34 CTR treatments did not differ significantly from each other in average percent stocking; both contained lower stocking levels than the Control treatment (Table 9). In general, across all treatments, the percent stocking became higher as time progressed, although no statistically significant increase occurred between 1983-1989 or 1994-2001 (Table 10; Figure 5).

Table 9. Average Percent Stocking by Treatment

Treatment	Mean	Standard Error
	……………………………(%)……………………………	
20 CTR	92.74_{a}	3.79
34 CTR	92.13_{a}	4.27
Control	108.94_{b}	2.89

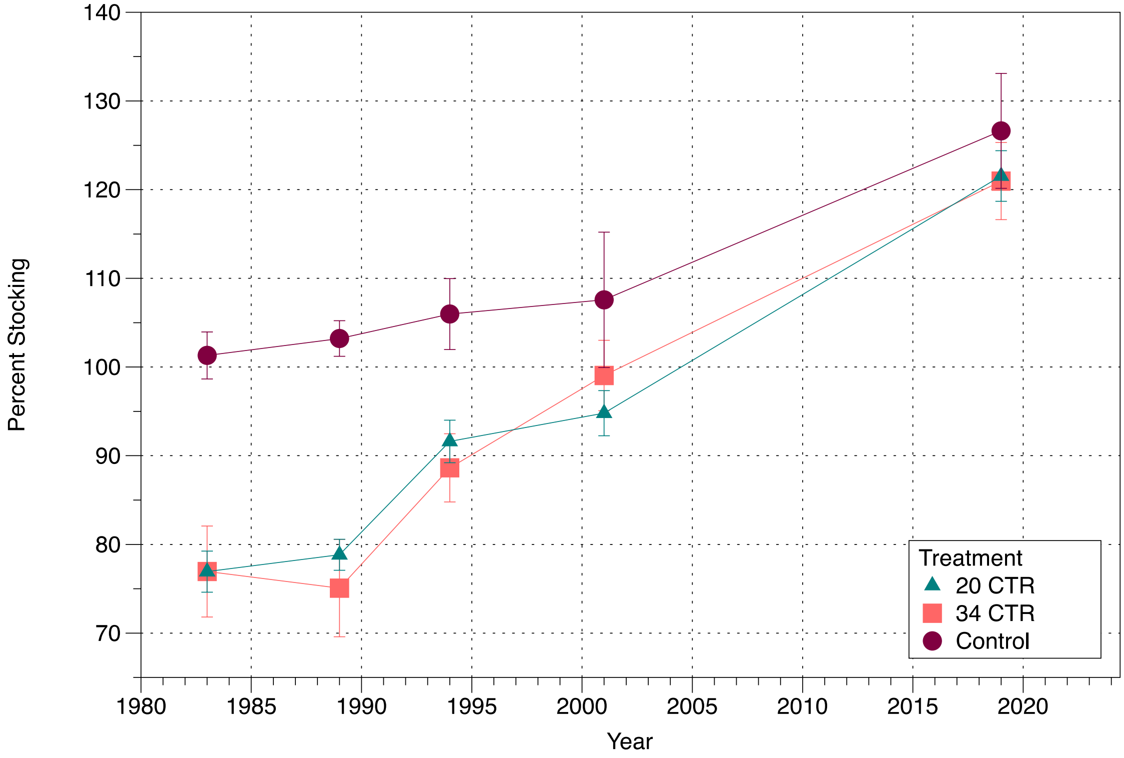
(Table 9: Average percent stocking (%) by treatment. Shared subscripts (a, b) indicate no statistical difference, while differing subscripts indicate a statistical difference.)

Table 10. Average Percent Stocking by Year

Year	Mean	Standard Error
	……………………………(%)……………………………	
1983	85.06_{a}	3.94
1989	85.70_{a}	4.19
1994	95.40_{b}	2.92
2001	100.47_{b}	3.14
2019	123.04_{c}	2.62

(Table 10: Average percent stocking (%) by year. Shared subscript (a, b, c) denote no statistical difference; differing subscripts denote a statistical difference exists.)

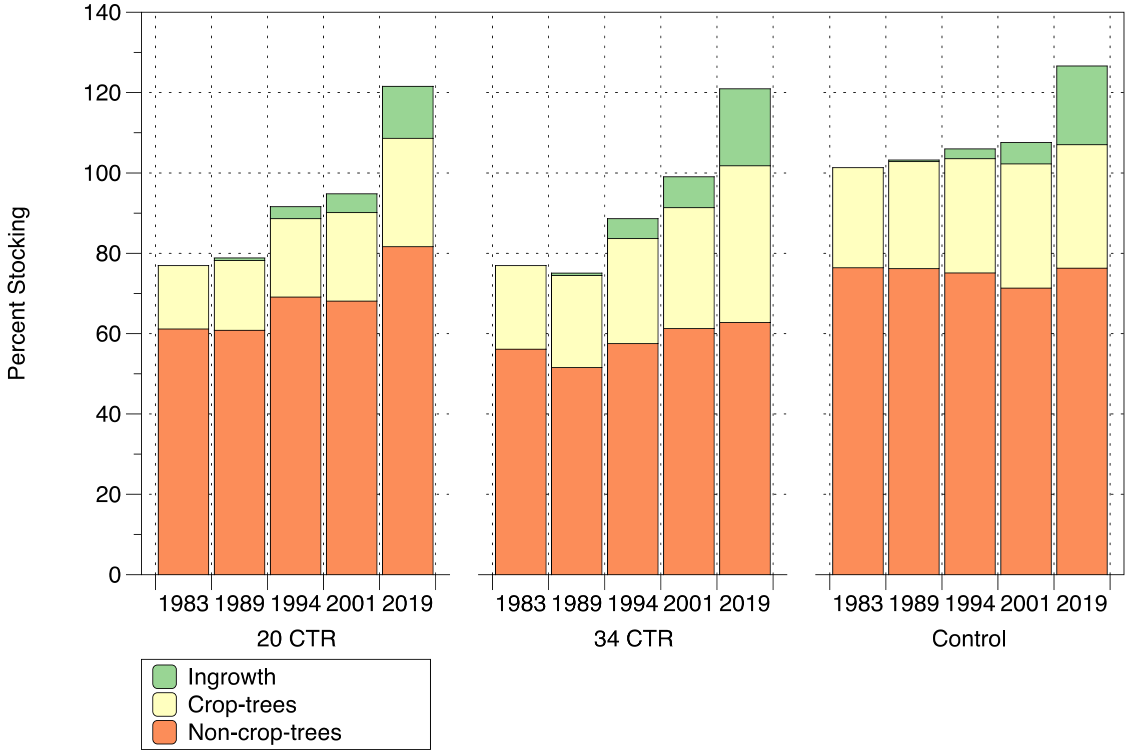
Figure 5. Average Percent Stocking Over Time by Treatment



(Figure 5: Average percent stocking by treatment over time)

Growth by crop-trees and ingrowth accounted for the majority of the increase in the average percent stocking in the 34 CTR treatment from 1983 to 2019, contributing 19% and 20%, respectively (Figure 6). The contribution of non-crop-trees increased only slightly over time for a total change of 6%. Increases in all three tree classifications contributed to the overall percent stocking increase in the 20 CTR treatment, with crop-trees contributing 11%, non-crop-trees 21%, and ingrowth 13%. In contrast, at 5%, the change in percent stocking contributed by crop-trees was minimal in the Control treatment. The percent stocking of ingrowth increased by 20% in the Control treatment from 1983 to 2019 and accounted for nearly all of the overall percent stocking increases in this treatment (Figure 6).

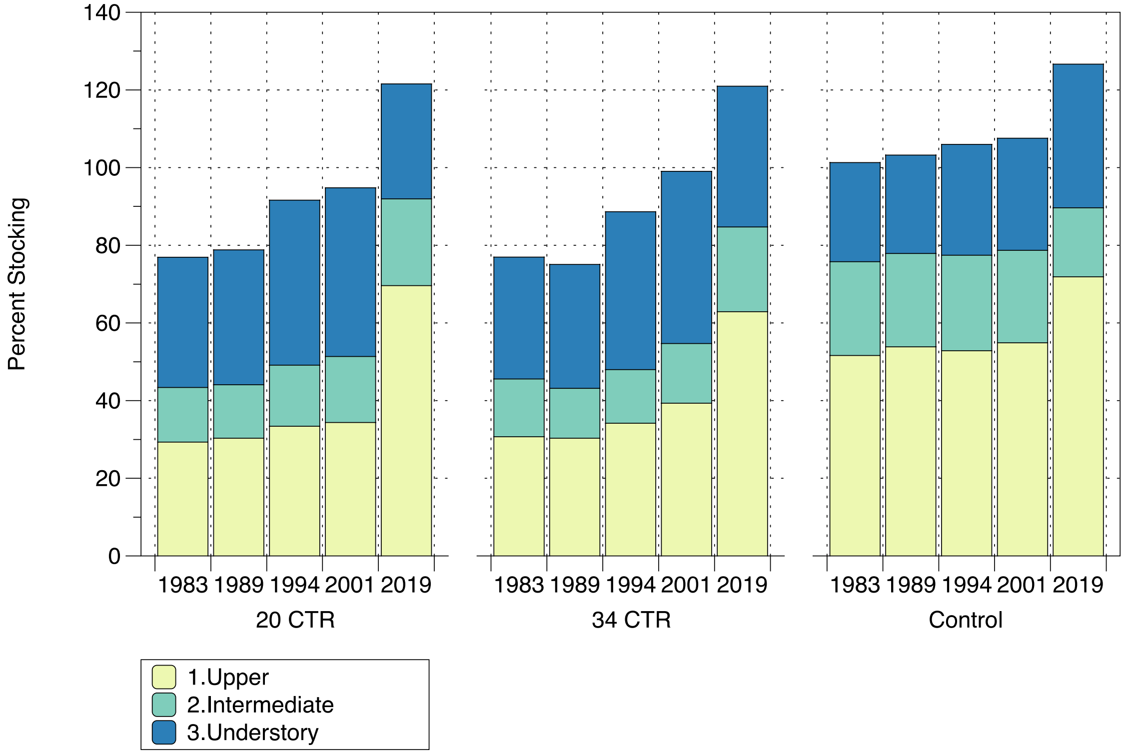
Figure 6. Average Percent Stocking by Tree Classification Over Time by Treatment



(Figure 6: Average percent stocking by tree classification (crop-trees, non-crop-trees, ingrowth) over time by treatment.)

For stand stocking in 1983, trees in the upper canopy (dominant and co-dominant crown classes) contributed 29% in the 20 CTR treatment, 31% in the 34 CTR treatment, and 52% in the Control treatment of the average percent stocking. By 2019, percent stocking of upper canopy trees was similar across treatments, increasing by 41% and 32 % in the 20 CTR and 34 CTR treatments, respectively, and by 20% in the Control treatment. The 20 CTR and 34 CTR treatments shared similar stocking levels of intermediate crown class trees, both about 15% in 1983 and increasing to about 22% in 2019. In contrast, intermediate trees in the Control treatment contributed 24% of the total percent stocking in 1983 and 18% in 2019. Between 1983 and 2019, the percent stocking contributed by understory (overtopped crown class) trees decreased by 4% in the 20 CTR treatment, and increased by 5% and 11% in the 34 CTR and Control treatments, respectively (Figure 7).

Figure 7. Average Percent Stocking by Crown Position Over Time by Treatment



(Figure 7: Average percent stocking by crown position including upper (dominant and co-dominant crown classes), intermediate (intermediate crown class), and understory (overtopped crown class) over time by treatment.)

4.7 Ingrowth

From 1983 to 2019, ingrowth contributed an average of 287.5 trees per acre in the 20 CTR treatment, 291 trees per acre in the 34 CTR treatment, and 362.5 trees per acre in the Control treatment (Table 11). However, ingrowth density was not statistically different among the among treatments.

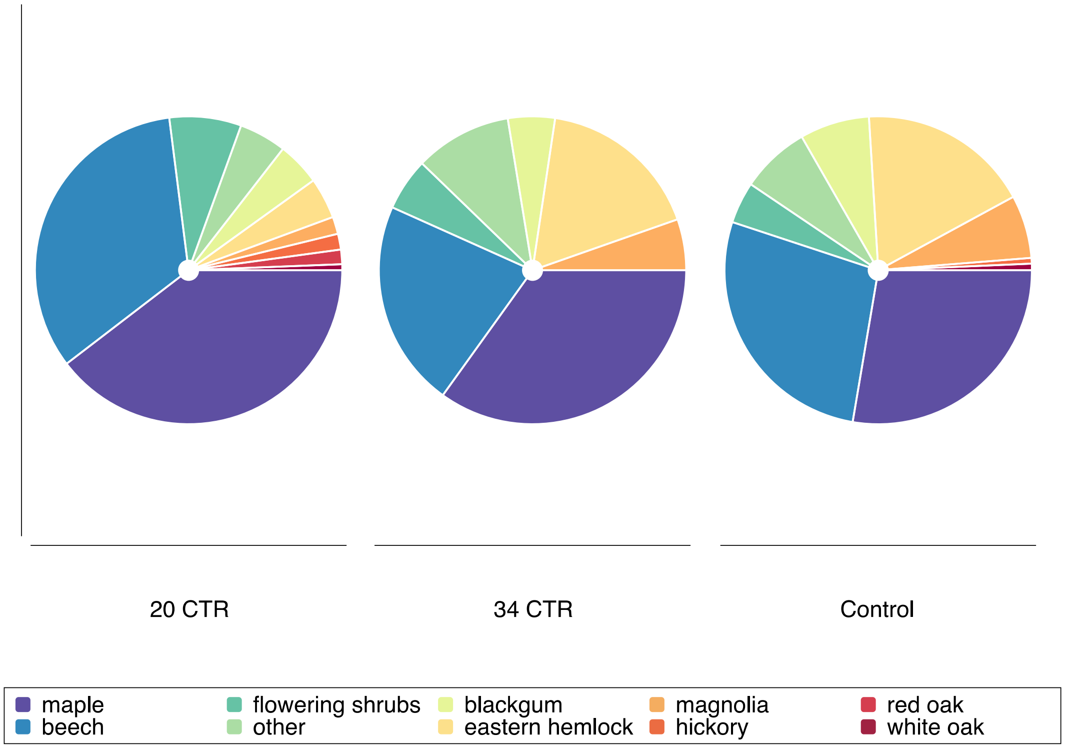
Table 11. Average Ingrowth by Treatment

Treatment	Mean	Standard Error
	……………………………(tpa)	……………………………
20 CT	287.5	47.40
34 CT	291.0	28.41
Control	362.5	69.09

(Table 11: Average ingrowth (tpa) by treatment.)

In general, maple (*Acer rubrum* and *Acer saccharum*) dominated the ingrowth, representing on average 42% and 35% of the ingrowth in the 20 and 34 CTR treatments respectively, and 30% in the Control treatment. Beech (*Fagus grandifolia*) was the second most common species among the ingrowth, making up 35% and 22% of the ingrowth in the 20 and 34 CTR treatments respectively, and 29% in the Control treatment. The maple and beech species groups combined accounted for more than half of the ingrowth regardless of the treatment (77% and 57% for the 20 and 34 CTR treatments, and 59% for the Control treatment). The ingrowth in the Control and 34 CTR treatments also contained a substantial amount of eastern hemlock (*Tsuga canadensis*), which accounted for 19% and 17% of all ingrowth, respectively. No other species accounted for more than 10% of the total ingrowth in any treatment (Figure 8).

Figure 8. Average Ingrowth by Species and Treatment



(Figure 8: Average ingrowth (%) from 1983-2019 by species and treatment.)

CHAPTER FIVE: DISCUSSION

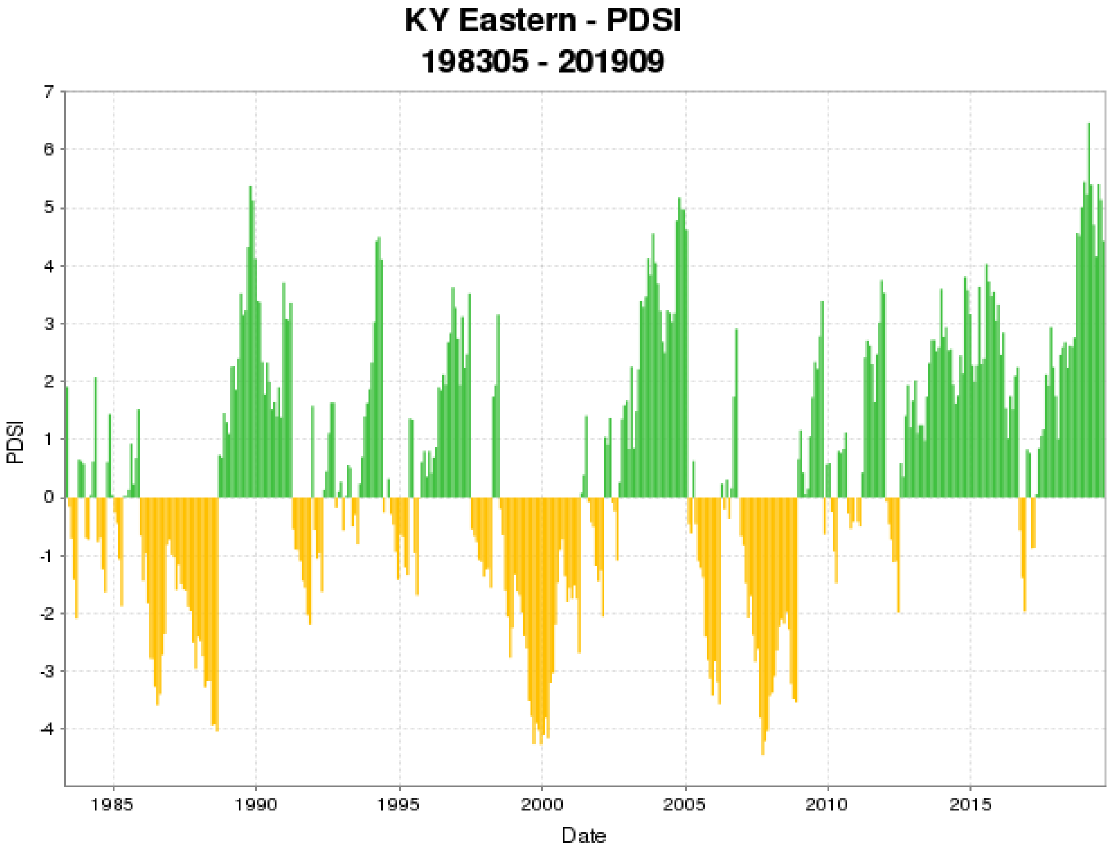
The results of this study contribute to the body of knowledge about CTR, clarifying aspects of the six questions offered by Trimble (1971). The study also contributes to the information available to forest managers and landowners about promoting oak sustainability. Despite encountering some difficulties in examining the effects of CTR on value at both the crop-tree level and the stand level, this study suggests that CTR promotes the growth and quality of white oak crop-trees in upland stands while stimulating growth on a stand level. CTR also shows promise as a tool to help sustain oak-dominated forests, even on small forestland holdings within complex management plans.

5.1 The Effects of Crop-tree Release on Crop-tree Growth and Quality

Fundamentally, CTR is an individual tree-focused treatment designed to increase the diameter growth of specific trees selected to meet management objectives. Its primary effects should be expected to be seen at the crop-tree level. The results of this study endorse this expectation. Regardless of the number of crop-trees released per acre, the average PAI dbh of released crop-trees was significantly greater than that of the unreleased crop-trees. Beyond the difference in the number of crop-trees selected, the 34 CTR treatment had smaller crop-trees on average than the 20 CTR and Control treatments. This highlights the tree-focused nature of CTR, indicating that crop-tree density as well as crop-tree size do not significantly alter the effects of CTR on the growth crop-trees.

Several studies note a delayed growth response following release for sawtimber red oaks (Graney 1998; Meadows 1998; Ward 2002); however, Beck (1987) observed immediate diameter growth of 85-year-old oaks following release. We found that the PAI dbh of white oak crop-trees was significantly lower in the first five years (1983-1989) following release than in the next two periods (1989-1994 and 1994-2001). While this could potentially be due to a lag in treatment response (as observed by others), the delay likely occurred in part as a result of a significant drought in the late 1980s. Chronic drought can reduce wood production in deciduous forests (Brzostek et al. 2014), and in non-limiting light conditions (such as those created by CTR), water stress has been shown to be a primary driver of decreased relative diameter growth in white oaks (Gauthier and Jacobs 2018). From April 1987 to May 1989, the Palmer Drought Severity Index, which uses precipitation and temperature data to estimate relative dryness, remained negative and dropped below -3 (threshold for severe drought) for the last 12 months of this period (Dai 2019) (Figure 9). A drought of this length and severity offers a plausible explanation for the lag in treatment response.

Figure 9. Palmer Drought Severity Index for Eastern Kentucky



(Figure 9: Palmer Drought Severity Index (PDSI) for Eastern Kentucky from May 1983 to September 2019. PDSI uses temperature and precipitation data to estimate relative dryness. Negative values indicate dryness and positive values wetness. https://www7.ncdc.noaa.gov/CDO/cdo. Accessed April 2020.)

The mean crop-tree growth results provide several insights into the application of CTR. Regarding Trimble's first question— "*At what age—or at what stage of stand development—should a crop-tree release be made?"*—the results of this study reveal that CTR can be applied to 70-80-year-old white oak dominated stands containing small sawtimber with positive growth outcomes. Ward (2008) suggests at least 90 years as an upper limit for applying CTR, reporting positive rates of growth after 12 years. Our results indicate that an upper limit of 90 years is within the realm of possibility and could potentially be exceeded. After 35 years, PAI dbh of crop-trees slowed, likely due to decreasing space for canopy spread, and the stand-wide percent stocking of the released treatments converged with that of the Control treatment. This indicates that CTR applied in a small sawtimber-sized white oak dominated stand promotes growth late into its rotation (over 100 years), highlighting the importance of biological life span of a species and the desired product in determining whether to release a stand. As a long-lived species associated with high value products such as veneer and stave logs, white oak makes a good candidate for CTR late in stand development.

The per-crop-tree growth results also clarify Trimble's second and third questions—*"How many crop-trees per acre should be selected?"* and "*What type of trees should be selected?"*. Although the number of crop-trees per acre that should be selected continues to depend on stand age and development, up to 34 crop-trees per acre can be selected in small sawtimber-sized stands. Smith et al. (1994) selected 40 and 60 black cherry or maple crop-trees per acre in a 65-year-old stand. They found that the dbh growth of crop-trees did not differ significantly among released and unreleased crop-trees until they compared only the 40 largest crop-trees for each plot. Considered together, these results indicate that no more than 30-40 crop-trees per acre should be released in small sawtimber-sized stands.

Multiple studies have demonstrated that CTR significantly increases the dbh growth of red oaks (Lamson and Smith 1978; Miller 2000; Schuler 2006; Ward 2002, 2008, 2013), but fewer studies have examined the effects of CTR on white oak (Morrissey et al. 2011; Sonderman 1987). Despite white oak growing slower than red oak in general (Gingrich 1967), our study demonstrates that it also responds well to CTR. Additionally, released white oak crop-trees as small as 8.3" and as large as 18.9" in dbh grew in diameter significantly more than unreleased white oak crop-trees (Miller and Stringer 2004). As to the question—"*What type of tree should be selected?"*—our results support the evidence that CTR promotes dbh growth for the white oak species and for crop-trees as small as 8" inches dbh.

One embedded uncertainty within the questions "*What method should we use to release crop-trees?; how heavy should be the release?"* is how CTR affects crop-tree quality. Although crop-trees typically respond best in terms of dbh growth to either a three- or four-sided release, the increased light levels can cause butt-log defects such as epicormic branching. For oaks in particular, epicormic branching can occur in CTR (Sonderman 1987), potentially reducing butt-log quality. Dale (1968) similarly notes that epicormic branching can be severe in heavily thinned young white oak stands, and white oak is in general prone to epicormic branching (Miller 1996). Given these concerns, we evaluated the effect of CTR on crop-tree quality in addition to crop-tree growth. In stark contrast to the idea that CTR might cause a loss of quality, our results indicate that CTR improves crop-tree quality. At year 17, the number of epicormic branches on crop-trees did not increase due to CTR (Miller and Stringer 2004). After 35 years, regardless of the number of crop-trees released, a significantly larger proportion of released crop-trees reached their MaxPG compared to unreleased crop-trees. Once again, these results highlight the tree-focused nature of CTR as crop-tree density did not alter the likelihood that a released crop-tree would reach its MaxPG.

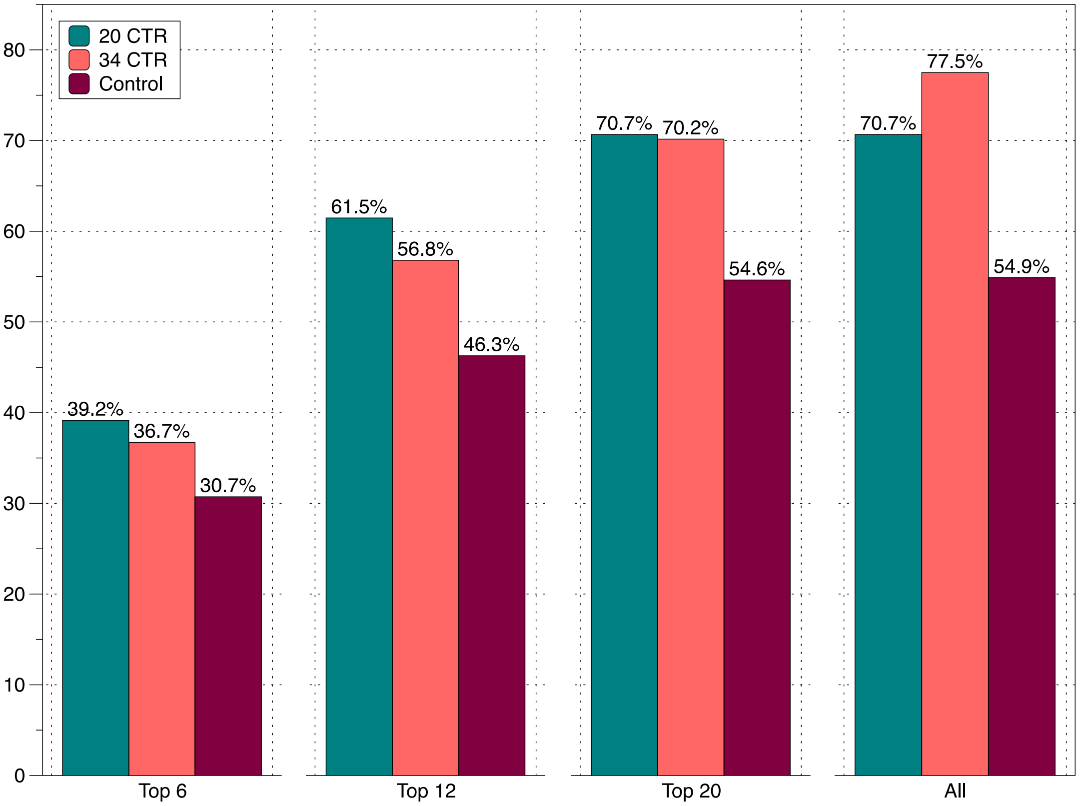
The financial aspects of CTR are not well-documented, and we encountered several hurdles in our financial analysis that inhibit reliable interpretation of the implications for forest management. No difference existed among the treatments in 2019 for average per-crop-tree value. Nevertheless, these results do not necessarily mean CTR does not increase the dollar-value of a crop-tree. Because CTR increases the PAI dbh of a crop-tree as well as the likelihood that a crop-tree will reach its MaxPG, the more likely financial outcome for

CTR is that a released crop-tree will be more valuable than if it is not released. Larger size and better quality should translate to a more valuable crop-tree.

The size discrepancy among the treatments (the 34 CTR treatment had a significantly smaller average dbh than the 20 CTR and Control treatments) did not mask the treatment effects on crop-tree growth in quality, but it did undermine our ability to parse out the management implications of the per-crop-tree value results. Size affects the value of a crop-tree in two ways. First, it determines the volume of a crop-tree. As the volume of a crop-tree increases, its value increases (assuming its stem quality is not reduced). Second, it determines the grade for which a crop-tree qualifies. Whereas volume change affects crop-tree value in a steady manner, a grade change causes a significant spike in crop-tree value. A small released crop-tree might substantially increase in size and never cross the diameter threshold for grade 2, while an unreleased crop-tree right at the diameter threshold for grade 2 might grow only a little and increase substantially in value. This dynamic does not preclude the possibility that CTR increases or maximizes the value of the small crop-tree, but it does create enough variability in the per-crop-tree value estimates to potentially mask the treatment effect. The discrepancy in the average stand age among treatments and the variability of site quality only confounded the uncertainty caused by size discrepancy. Ultimately, the hurdles we encountered reinforced the fact that the value of a tree varies with site and with the local market. Even if we were able to assign a reliable dollar amount to a released crop-tree, this information would be of limited use to a forester or landowner managing a different stand in a different market.

The effect of the size discrepancy on per-crop-tree value raises a warning flag for selecting too many crop-trees. Although site quality and stand age likely contributed to the size discrepancy, the primary reason that the 34 CTR treatment had a smaller average crop-tree diameter than the other treatments is that crop-trees that met the requirements became increasingly difficult to find when the number increased from 20 crop-trees per acre to 34 crop-trees per acre. A compromise had to be made, and small crop-trees, some so small that they never reached the grade 3 diameter class despite exhibiting substantial growth, had to be released. This likely contributed to the divergence seen in crop-tree butt-log value between the released treatments. The 20 CTR treatment had an average crop-tree butt-log value nearly double that of the 34 CTR treatment; however, the two treatments did not significantly differ in PAI dbh or the proportion of crop-trees reaching their MaxPG, indicating that the divergence comes from a factor other than dbh growth or quality. The smaller size of crop-trees in the 34 CTR treatment likely appreciably reduced the average crop-tree value in those stands. Consistent with this theory, the 20 most valuable crop-trees in either released treatment represent on average 70% of the total stand value per acre in 2019. The remaining 14 crop-trees per acre only increase the contribution another 7% (Figure 10).

Figure 10. Percent of Total Stand Value per Acre Accounted for by Crop-trees



(Figure 10: Percent of total stand value per acre accounted for by the most valuable 6, 12, and 20 crop-trees per acre as well as all crop-trees per acre by treatment.)

Additionally, smaller white oak crop-trees exhibited a greater proclivity for epicormic branching than larger white oak crop-trees 17 years after release (Miller and Stringer 2004). Although up to 34 crop-trees per acre can be released with positive outcomes for diameter growth, selecting fewer crop-trees avoids the compromise of selecting crop-trees that might not be worth releasing.

5.2 The Effects of Crop-tree Release on Stand Structure and Value

Although CTR is a tree-focused treatment, applying it has stand-wide implications. For example, Ward (2017) found CTR resulted in increased upper canopy persistence and increased diameter growth for partially released non-crop-trees. The stand-level effects of

CTR matter for a couple of reasons. When it comes time to harvest, the entire stand takes precedence. Crop-trees contribute significantly to the stand, but they cease to be the sole focus for foresters or landowners. Additionally, the widespread shift from oak-dominated forests to late-successional forests is occurring at the stand-level not at a tree-level. When considering any oak-focused silvicultural treatment at this point in the history of the forest of the eastern U.S., the possibilities of the treatment to contribute to the regeneration and recruitment of oak needs to examined.

At the outset of this study—congruent with the tree-focused nature of CTR—the questions asked concentrated entirely on crop-trees. Concerns around oak regeneration and recruitment were in their infancy thirty-five years ago, and questions about the effectiveness of CTR for white oak crop-trees took precedence over questions about the ability of CTR to preserve oak sustainability. Since then, issues concerning the regeneration and recruitment of oak have increasingly preoccupied the world of oak silviculture. Fortunately, we were able to ask some stand-level questions within the confines of this study.

The stand NPV per acre analysis encountered similar hurdles to the per-crop-tree value analysis. By chance, the Control treatment tended to be older with larger diameters in 1983 than the trees in the release treatments. The variability of age and size among plots affected the grades assigned to the non-crop-trees. A younger tree with a smaller diameter might not qualify for a grade even if CTR positively affected the growth and quality of the tree. The NPV per acre combines volume and grade—both of which contain underlying issues due to tree size. Add to this the variability in site quality and age among stands, and the NPV per acre results become difficult to interpret regarding their management implications.

The basal area per acre and percent stocking provides a better picture of the influence of CTR at a stand level. Post-treatment, both the 20 CTR and 34 CTR treatments were significantly smaller in average BA per acre than the Control treatment. This difference continued across time until the fifth measurement in 2019, when no significant difference existed among treatments. These results suggest that the stands undergoing CTR grew at an increased rate over the 35 years between the release and the end of the rotation. The average percent stocking supports this interpretation. In 1983, after treatment, the 20 CTR and 34 CTR treatments averaged approximately 76% stocking. Prior to treatment, both treatments were overstocked on average. The change in percent stocking due to the application of CTR resembles the change created by a light area-wide thinning. Although CTR did not reduce the percent stocking to the recommended 60-70% (Roach and Gingrich 1968), the immediate environment around the crop-trees was characteristic of a lower stand density than indicated by the percent stocking (Miller and Stringer 2004). In 2019, the released treatments reached the upper limits of stand stocking and converged with the Control treatment. Ingrowth contributed the majority of the total change in percent stocking for the Control treatment. In contrast, crop-trees and non-crop-trees contributed the majority of the total change in percent stocking in the released treatments, indicating that CTR not only provides growing space for crop-trees but also promotes stand-wide growth.

Dey (2014) has called regeneration and recruitment the pillars of oak sustainability. Even though CTR is not designed to address the growth and persistence of regeneration, it has shown promise as a tool to foster oak recruitment in stands at the stem exclusion stage (Ward 2013). In the older, small sawtimber-sized stands in this study, CTR focuses on crop-tree growth and improvement over directly addressing oak regeneration and recruitment. Ingrowth was strikingly similar among treatments. CTR did not cause a significant increase of ingrowth, and the species composition of the ingrowth appeared similar across treatments. Maple and beech comprise nearly half of the ingrowth in every treatment. The one incongruence in these results is the abundance of eastern hemlock in the Control and 34 CTR treatments. Likely, site anomalies or the increased shade from more intact canopies versus the 20 CTR treatment contributed to this.

The similarities among treatments with regards to ingrowth indicates that CTR by itself neither promotes or diminishes oak regeneration and recruitment. Nevertheless, CTR can contribute to oak sustainability, even in older stands. Because CTR reduces the density of the forest canopy, it may feasibly create better light conditions for oak regeneration and recruitment. After 15 years, the 20 CTR treatment developed twice the amount of white oak advanced regeneration as the other treatments, and both released treatments produced significantly taller white oak advanced regeneration than the Control treatment; however, without addressing competition from shade-tolerant species in the understory, a harvest would likely not regenerate white oak (Stringer 1999). Additionally, it preserves and nurtures oak seed sources by removing competing tree species from the canopy, allowing oak canopies to expand and thicken (Brooke et al. 2018). Rate of diameter growth has been linked to the longevity of white oaks, and if annual dbh growth drops below 0.02 inches, mortality rates can significantly increase (Shifley et al. 2006). Because of this, Lhotka et al. (2016) suggest CTR as a tool to enhance the longevity of oaks in the upper canopy. As oak-dominated forests continue to age, silvicultural treatments that reduce mortality, maintain oak seed supply, and control stand densities will be vital to oak sustainability.

5.3 Closing Remarks

Crop-tree release applied to small sawtimber-sized upland white oak stands increases crop-tree diameter growth as well as the likelihood that a crop-tree will reach its maximum potential grade. It also stimulates stand-wide growth without altering the patterns of ingrowth. Schuler (2006) maintains that CTR might imitate past disturbance regimes, marked by oaks experiencing periods of suppression and release, that led to old-growth oak forests. Research looking at CTR applied at mid- to late-rotation combined with silvicultural treatments that focus on understory conditions (e.g. prescribed fire) would help elucidate the potential of CTR to create canopy densities that promote oak regeneration and recruitment given favorable understory conditions for oak. As oak-dominated forests are being replaced by late-successional forests across the eastern U.S., landowners and foresters need silvicultural tools that focus on active oak management.

As forestland holdings become increasingly small and forest family owners adopt a variety of management goals, forest managers face new social complexities. CTR shows promise in promoting active oak management within these complexities. It is scalable across forestland sizes and across varying markets. Small-scale forestry lacks the economies of scale and market power which large-scale forestry enjoys (Herbohn 2006). Managers and landowners practicing forestry in small forestland holdings need silvicultural treatments that maximize production while minimizing production costs. A commercial CTR in small-sawtimber sized stands could achieve this, depending on local markets and stand development. CTR also fits well within management plans with multiple objectives outside of timber. Ward (2008) observes the aesthetic appeal of stands post-CTR and argues that CTR is a suitable management practice for landowners who value non-commodity aspects of their forest. Additionally, CTR meets the increased public desire for partial cutting, making it desirable for landowners who value high forest cover (Ward 2002, 2008). Ward (2008) also argues that CTR makes a good introduction to forest management for landowners, highlighting another benefit of CTR—it is accessible. While traditional area-wide thinning requires knowledge of stand density concepts (such as percent stocking and basal area) as well as thinning methods (such as “thinning from below” or “crown thinning”), understanding CTR only requires a landowner to be able to recognize a high-quality tree. The treatment itself is also fairly straightforward: remove the trees that touch the crop-tree’s canopy. Oak sustainability requires active-management, and the accessibility of forest management for landowners matters. Widespread separation from the natural world undermines the ethical and empirical foundation for stewardship (Nadkarni et al. 2017). Perhaps the first step in sustaining oak is simply connecting landowners with their forest.

APPENDIX A: PRE AND POST TREATMENT TABLES

Table 1a. Pre-treatment Summaries and Removed Trees Summaries by Plot

					Pre-treatment							Removed		
Plot	Treatment	SI	Age (yr)	dbh (in)	qmd (in)	tpa	BA (ft2)	Percent stocking	Volume (bf)	dbh (in)	qmd (in)	tpa	BA (ft2)	Volume (bf)
1	20 CTR	75	81	3.27	4.93	796	105.31	101.42	3329.64	12.25	12.65	38	33.17	1365.51
4	20 CTR	83	67	3.57	5.34	692	107.63	101.02	3549.90	12.36	12.93	36	32.85	1415.41
7	20 CTR	68	70	3.42	4.82	780	99.00	98.85	2239.70	8.83	9.25	36	16.80	374.14
8	20 CTR	69	65	3.81	5.18	660	96.45	95.40	2292.62	10.88	11.57	34	24.81	946.99
2	34 CTR	76	72	3.55	5.40	732	116.34	108.03	3865.97	11.64	12.27	66	54.17	2181.28
3	34 CTR	65	62	3.64	4.83	784	99.71	102.46	2057.33	9.03	9.82	54	28.42	856.78
5	34 CTR	74	52	4.20	5.06	758	105.76	111.71	1065.41	7.95	8.25	66	24.51	352.39
10	34 CTR	77	82	2.98	4.87	820	105.88	98.93	4083.22	13.00	13.33	28	27.13	1223.39
6	Control	69	70	4.13	5.77	634	115.18	108.16	3513.23	-	-	-	-	-
9	Control	69	80	3.36	5.15	738	106.85	100.50	3589.55	-	-	-	-	-
11	Control	75	99	3.18	5.07	776	108.95	101.32	4156.33	-	-	-	-	-
12	Control	77	82	4.83	6.85	422	108.07	95.26	4026.92	-	-	-	-	-

Table 12: Summaries of plots pre-treatment in 1983 and summaries of trees removed in 1983 in released plots. Variables include site index (SI, age = 50), age in years, dbh in inches, quadratic mean diameter (qmd) in inches, trees per acre (tpa), basal area (BA) per acre in square feet, percent stocking, and butt-log volume per acre in Doyle log rule board feet (bf)

Table 2a. Post-treatment Summaries by Plot

						Post-treatment			
Plot	Treatment	SI	Age (yr)	dbh (in)	qmd (in)	tpa	BA (ft_2)	Percent stocking	Volume (bf)
1	20 CTR	75	81	2.82	4.18	758	72.14	74.43	1964.12
4	20 CTR	83	67	3.09	4.57	656	74.77	74.55	2134.49
7	20 CTR	68	70	3.16	4.50	744	82.20	83.86	1865.57
8	20 CTR	69	65	3.43	4.58	626	71.64	74.87	1345.63
2	34 CTR	76	72	2.75	4.14	666	62.17	63.84	1684.69
3	34 CTR	65	62	3.24	4.23	730	71.30	77.94	1200.55
5	34 CTR	74	52	3.84	4.64	692	81.25	88.88	713.01
10	34 CTR	77	82	2.63	4.27	792	78.75	77.12	2859.83
6	Control	69	70	4.13	5.77	634	115.18	108.16	3513.23
9	Control	69	80	3.36	5.15	738	106.85	100.50	3589.55
11	Control	75	99	3.18	5.07	776	108.95	101.32	4156.33
12	Control	77	82	4.83	6.85	422	108.07	95.26	4026.92

Table 13: Summaries of plots prost-treatment in 1983. Variables include site index (SI, age = 50), age in years, dbh in inches, quadratic mean diameter (qmd) in inches, trees per acre (tpa), basal area (BA) per acre in square feet, percent stocking, and butt-log volume per acre in Doyle log rule board feet (bf)

Table 3a. Pre-treatment Summaries and Removed Trees Summaries by Treatment

Pre-treatment									Removed				
Treatment	SI	Age	dbh	qmd	tpa	BA	Percent stocking	Volume	dbh	qmd	tpa	BA	Volume
		(yr)	(in)	(in)		(ft2)		(bf)	(in)	(in)		(ft2)	(bf)
20 CTR	73.75	70.75	3.52	5.07	732	102.10	99.17	2852.96	11.08	11.60	36	26.91	1025.51
34 CTR	73	67	3.59	5.04	773.5	106.92	105.28	2767.981	10.41	10.92	53.5	33.55	1153.46
Control	72.5	82.75	3.87	5.71	642.5	109.76	101.31	3821.51	-	-	-	-	-

Table 14: Pre-treatment summaries and summaries of removed trees in release treatments by treatment in 1983. Variables include site index (SI, age = 50), age in years, dbh in inches, quadratic mean diameter (qmd) in inches, trees per acre (tpa), basal area (BA) per acre in square feet, percent stocking, and butt-log volume per acre in Doyle log rule board feet (bf)

Table 4a. Post-treatment Summaries by Treatment

Post-treatment								
Treatment	SI	Age	dbh	qmd	tpa	BA	Percent stocking	Volume
		(yr)	(in)	(in)		(ft2)		(bf)
20 CTR	73.75	70.75	3.12	4.46	696	75.19	76.93	1827.45
34 CTR	73	67	3.12	4.32	720	73.37	76.94	1614.52
Control	72.5	82.75	3.87	5.71	642.5	109.76	101.31	3821.51

Table 15: Post-treatment summaries by treatment in 1983. Variables include site index (SI, age = 50), age in years, dbh in inches, quadratic mean diameter (qmd) in inches, trees per acre (tpa), basal area (BA) per acre in square feet, percent stocking, and butt-log volume per acre in Doyle log rule board feet (bf)

APPENDIX B: CROP-TREE FIGURES AND SUMMARY STATISTICS

Figure 1b. Average Crop-tree Dbh (inches) by Treatment Over Time

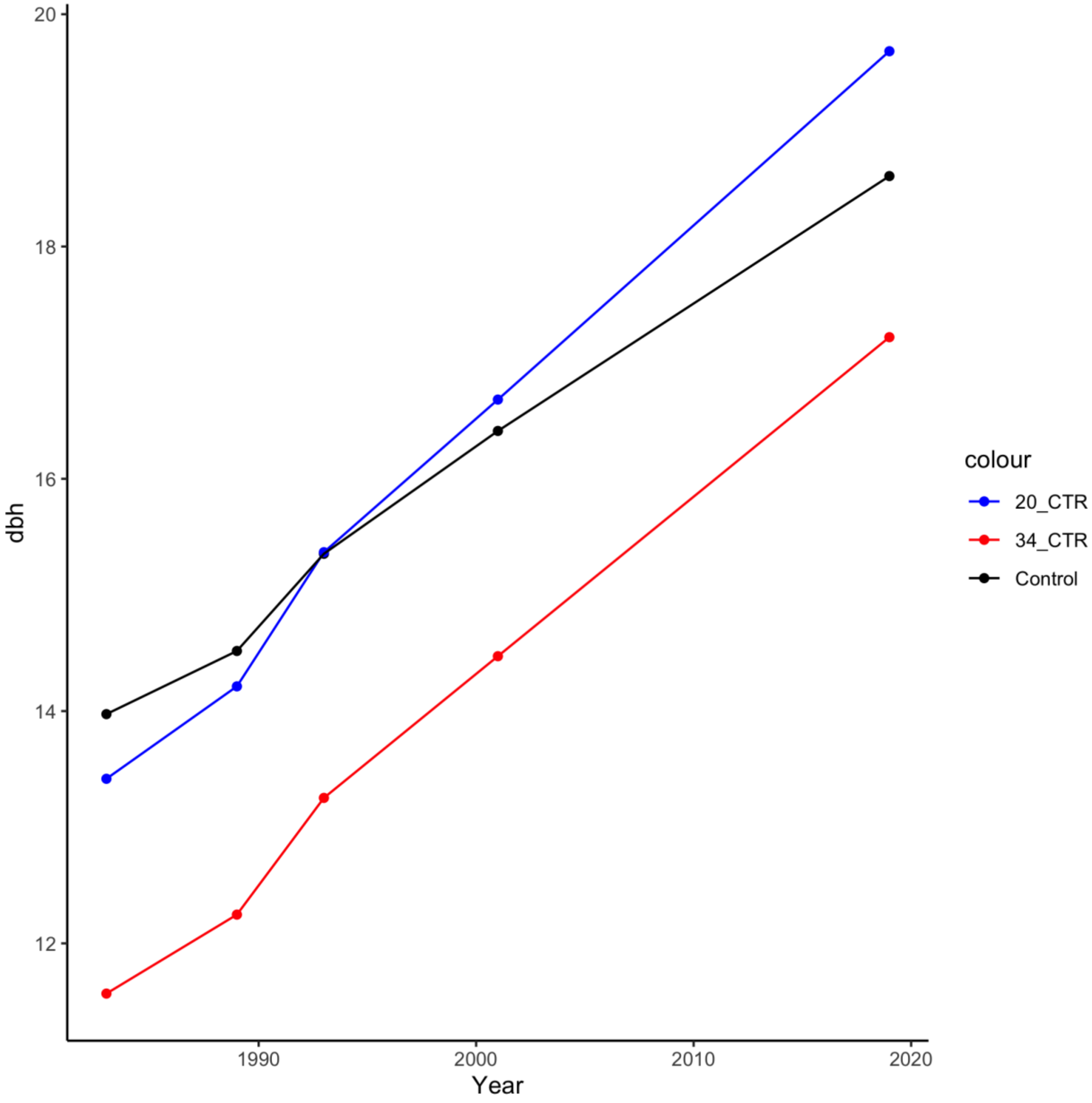


Table 1b. Average Crop-tree Dbh (inches) by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	11.37	12.05	13.37	14.74	15.56	13.42	1.93
	1989	12.02	12.81	14.23	15.64	16.38	14.21	2.02
	1994	12.96	13.89	15.54	17.02	17.44	15.37	2.14
	2001	14.19	15.19	16.99	18.48	18.56	16.68	2.18
	2019	16.59	18.07	20.17	21.78	21.80	19.68	2.56
34 CTR	1983	9.04	9.51	11.29	13.34	14.65	11.57	2.66
	1989	9.67	10.24	12.00	14.01	15.32	12.25	2.66
	1994	10.62	11.28	13.03	15.00	16.33	13.25	2.66
	2001	12.00	12.45	14.14	16.16	17.62	14.47	2.64
	2019	14.33	15.26	17.18	19.15	20.19	17.22	2.73
Control	1983	13.43	13.75	14.08	14.31	14.31	13.97	0.42
	1989	14.10	14.29	14.55	14.78	14.86	14.52	0.35
	1994	14.99	15.12	15.37	15.60	15.70	15.35	0.33
	2001	15.88	16.29	16.52	16.63	16.74	16.41	0.38
	2019	17.61	18.21	18.75	19.15	19.31	18.61	0.77

Figure 2b. Average Crop-tree Quadratic Mean Diameter (inches) by Treatment Over Time

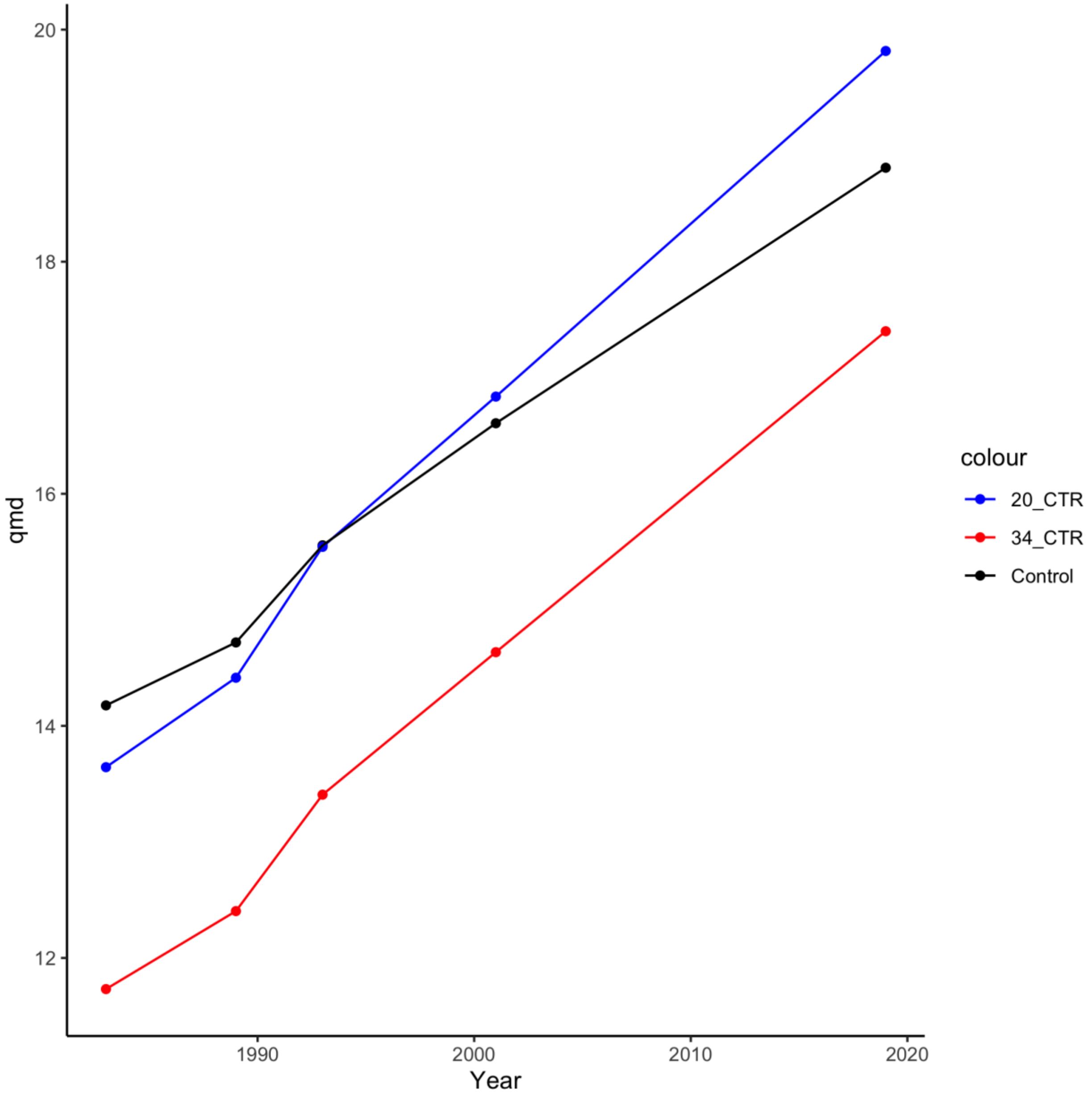


Table 2b. Average Crop-Tree Quadratic Mean Diameter (inches) by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	11.50	12.16	13.55	15.03	15.97	13.64	2.06
	1989	12.15	12.91	14.38	15.88	16.75	14.41	2.13
	1994	13.09	13.98	15.66	17.22	17.77	15.54	2.22
	2001	14.32	15.28	17.08	18.64	18.87	16.84	2.23
	2019	16.74	18.18	20.27	21.91	21.98	19.82	2.57
34 CTR	1983	9.15	9.76	11.52	13.49	14.75	11.73	2.63
	1989	9.76	10.45	12.22	14.17	15.42	12.40	2.63
	1994	10.72	11.47	13.23	15.17	16.44	13.41	2.65
	2001	12.11	12.65	14.34	16.33	17.74	14.64	2.63
	2019	14.47	15.47	17.40	19.33	20.33	17.40	2.72
Control	1983	13.79	14.01	14.24	14.41	14.44	14.18	0.30
	1989	14.46	14.56	14.74	14.90	14.94	14.72	0.23
	1994	15.24	15.46	15.61	15.70	15.77	15.56	0.24
	2001	16.13	16.56	16.74	16.79	16.81	16.61	0.32
	2019	17.90	18.35	18.84	19.30	19.65	18.81	0.77

Figure 3b. Basal Area (ft2) Per Acre of Crop-trees by Treatment Over Time

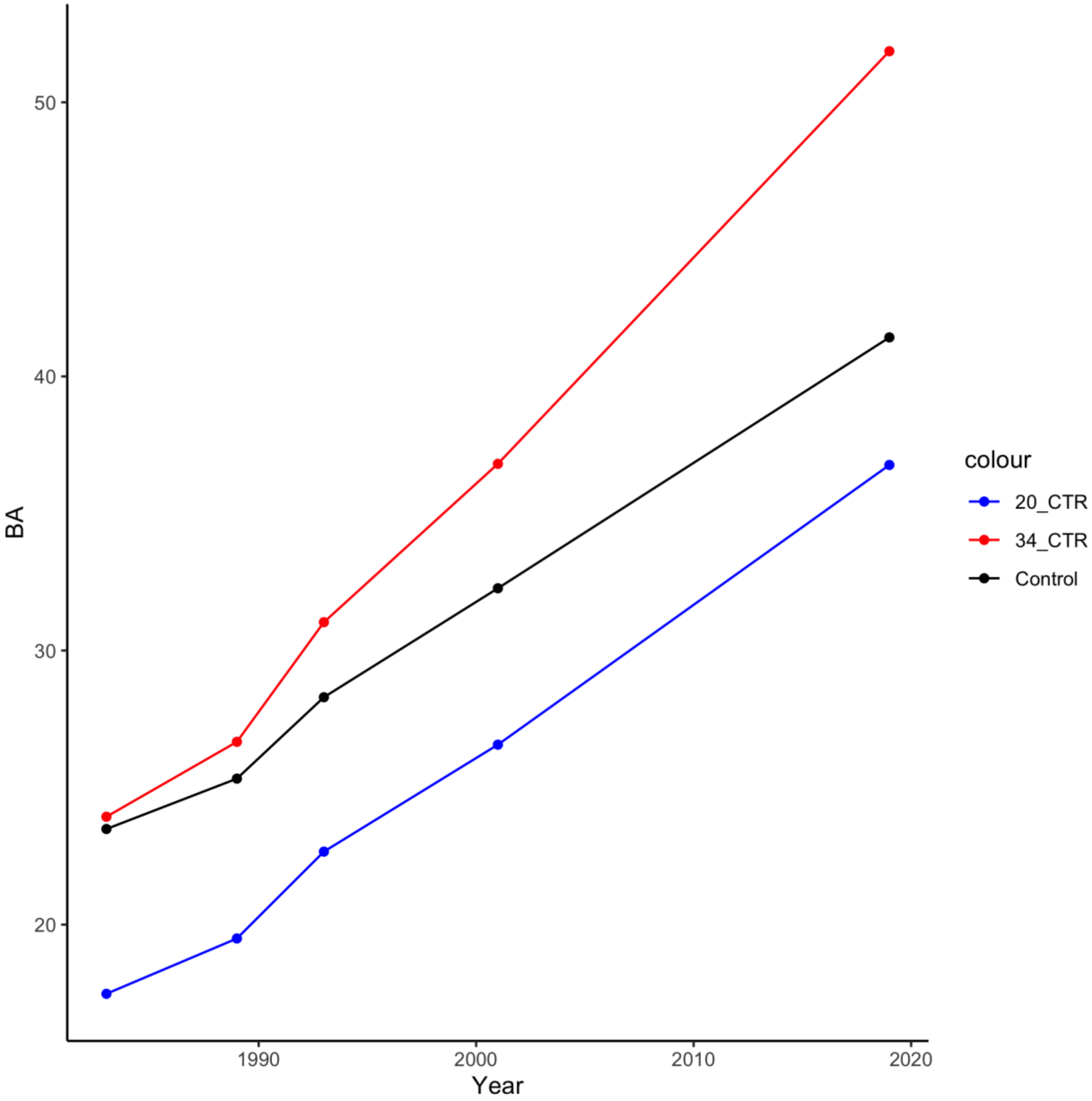


Table 3b. Basal Area (ft$_2$) Per Acre of Crop-trees by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	12.99	13.28	17.32	21.52	22.27	17.48	4.97
	1989	14.48	14.97	19.50	24.02	24.50	19.49	5.42
	1994	16.81	17.55	22.68	27.79	28.48	22.66	6.21
	2001	20.13	20.97	26.16	31.75	33.82	26.57	6.89
	2019	27.51	29.65	36.27	43.38	47.03	36.77	9.33
34 CTR	1983	14.60	15.82	23.96	32.08	33.22	23.94	9.88
	1989	16.64	18.17	26.87	35.37	36.30	26.67	10.45
	1994	20.07	21.89	31.39	40.54	41.28	31.03	11.31
	2001	25.61	26.58	36.79	47.02	48.05	36.81	12.21
	2019	36.54	39.81	52.02	64.08	66.87	51.86	15.36
Control	1983	18.08	23.18	24.94	25.25	25.98	23.49	3.64
	1989	19.47	24.82	26.99	27.50	27.86	25.33	3.94
	1994	21.71	27.56	29.95	30.69	31.58	28.30	4.47
	2001	24.67	31.26	33.76	34.78	36.89	32.27	5.28
	2019	32.11	38.83	41.52	44.11	50.55	41.42	7.54

Figure 4b. Percent Stocking of Crop-trees by Treatment Over Time

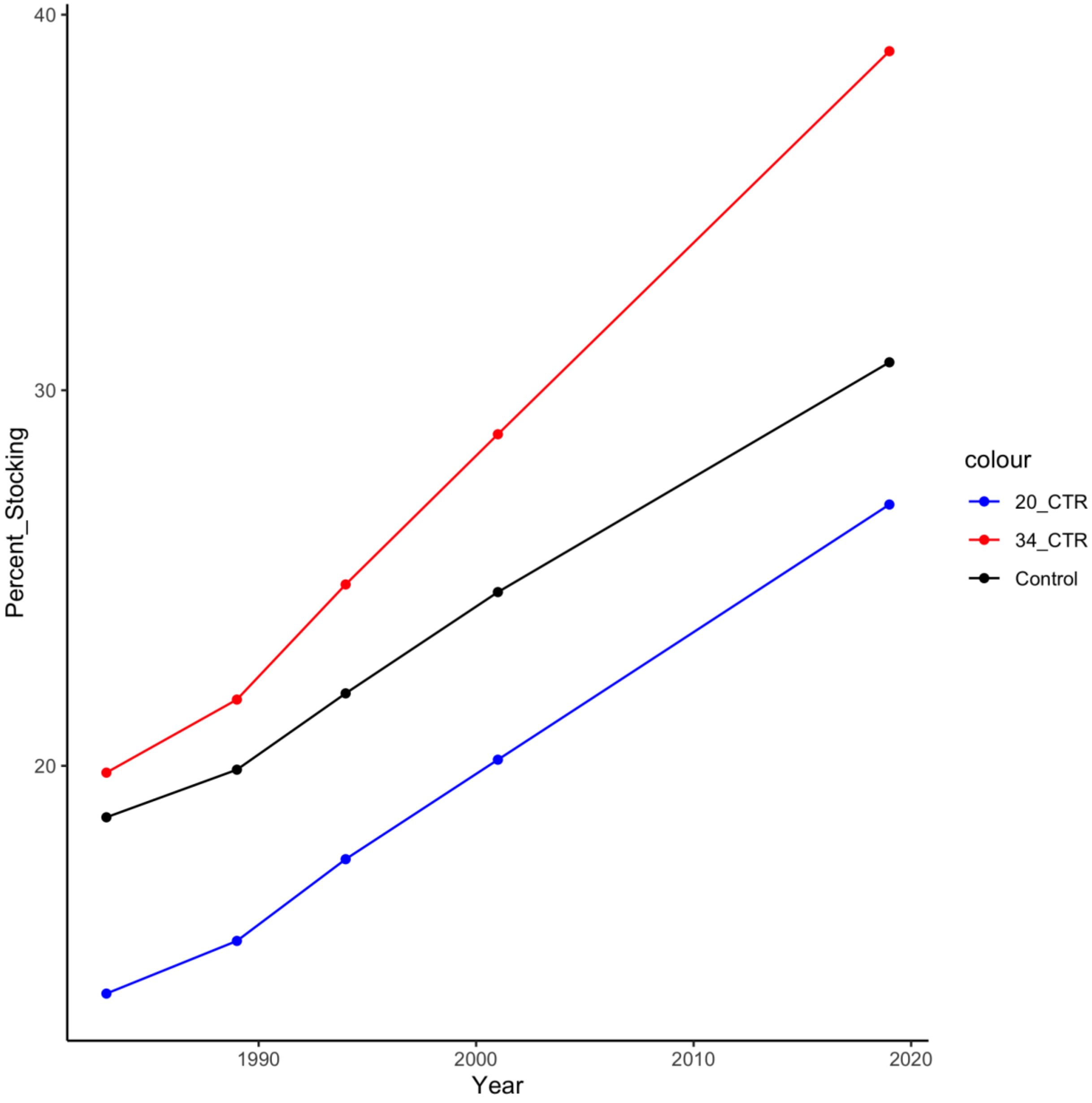


Table 4b. Percent Stocking of Crop-trees by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	10.93	11.01	13.86	16.79	17.09	13.94	3.42
	1989	12.00	12.20	15.37	18.51	18.61	15.34	3.70
	1994	13.64	14.00	17.40	20.91	21.62	17.51	4.22
	2001	15.95	16.35	19.75	23.56	25.21	20.16	4.65
	2019	20.97	22.20	26.48	31.23	33.90	26.96	6.18
34 CTR	1983	13.24	13.96	19.95	25.81	26.13	19.82	7.06
	1989	14.76	15.70	22.03	28.09	28.24	21.76	7.38
	1994	17.27	18.40	25.20	31.62	31.65	24.83	7.88
	2001	21.24	21.74	28.95	36.04	36.16	28.83	8.38
	2019	28.86	30.88	38.85	47.01	49.55	39.03	10.34
Control	1983	14.32	18.40	19.79	20.01	20.62	18.63	2.90
	1989	15.27	19.46	21.20	21.63	21.92	19.90	3.12
	1994	16.80	21.34	23.25	23.84	24.41	21.93	3.48
	2001	18.81	23.85	25.84	26.62	28.02	24.63	4.02
	2019	23.77	28.92	31.04	32.86	37.13	30.74	5.47

Figure 5b. Butt-log Volume (board feet, Doyle) Per Crop-tree by Treatment Over Time

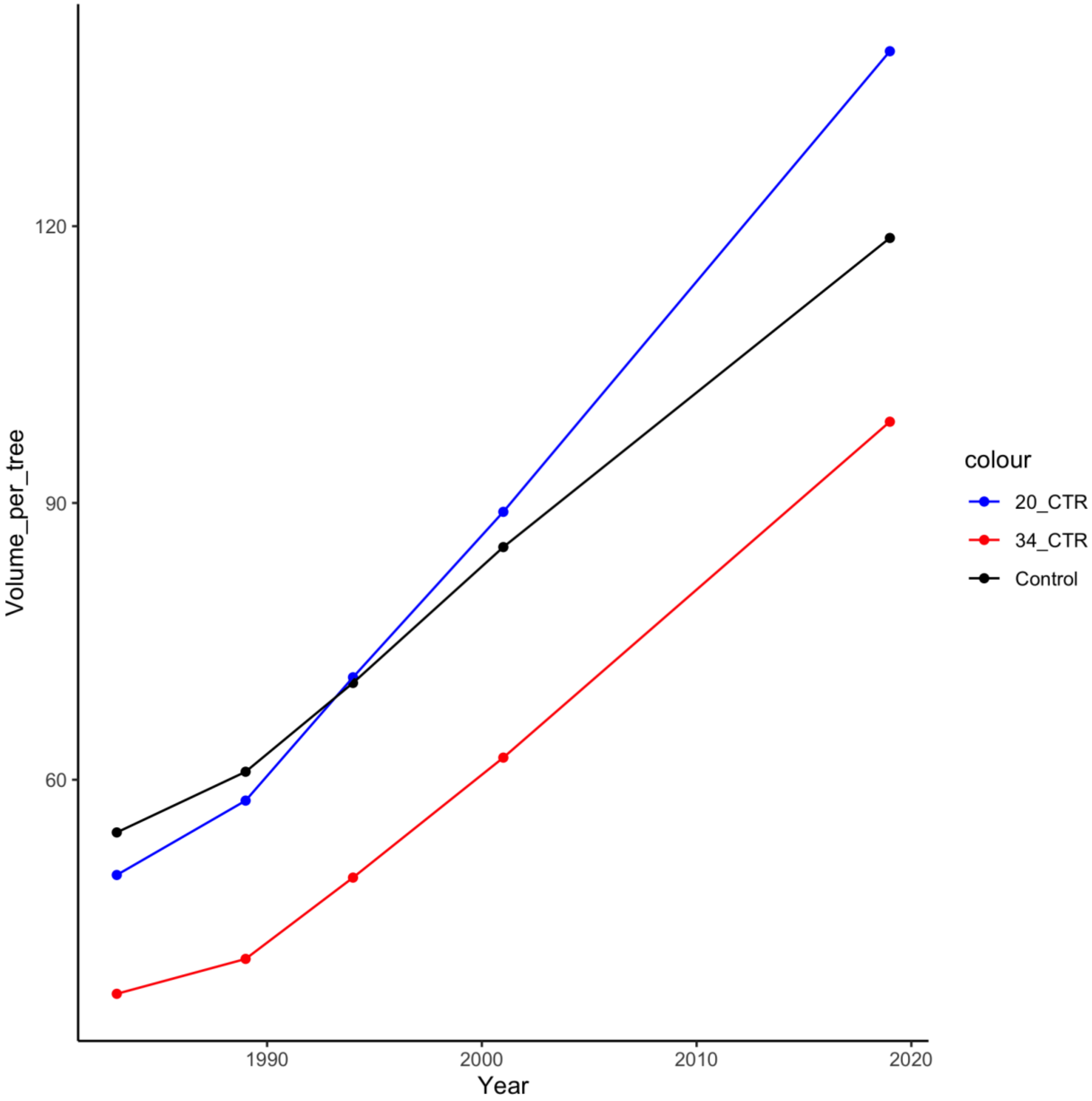


Table 5b. Butt-log Volume (board feet, Doyle) Per Crop-tree by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	30.67	32.50	46.00	63.17	76.04	49.68	21.72
	1989	33.78	38.97	55.16	73.93	86.86	57.74	24.86
	1994	40.02	49.55	71.15	92.70	102.09	71.10	29.47
	2001	53.46	65.16	91.33	115.20	120.04	89.04	32.81
	2019	85.26	107.67	145.75	177.04	179.10	138.97	46.41
34 CTR	1983	18.55	27.28	35.17	44.68	58.30	36.80	16.83
	1989	19.04	26.74	38.28	52.12	66.73	40.58	20.97
	1994	24.93	31.16	45.97	64.21	80.70	49.39	25.34
	2001	33.90	40.13	57.70	79.97	100.28	62.40	30.40
	2019	55.25	68.41	97.13	127.53	145.72	98.81	41.98
Control	1983	52.72	53.71	54.42	55.00	55.59	54.29	1.22
	1989	60.25	60.45	60.68	61.09	61.86	60.87	0.71
	1994	69.83	70.19	70.43	70.73	71.28	70.49	0.61
	2001	83.44	84.11	85.12	86.23	87.19	85.22	1.66
	2019	103.98	110.41	118.38	126.69	134.16	118.72	13.21

Figure 6b. Butt-log Volume (board feet, Doyle) Per Acre of Crop-trees by Treatment Over Time

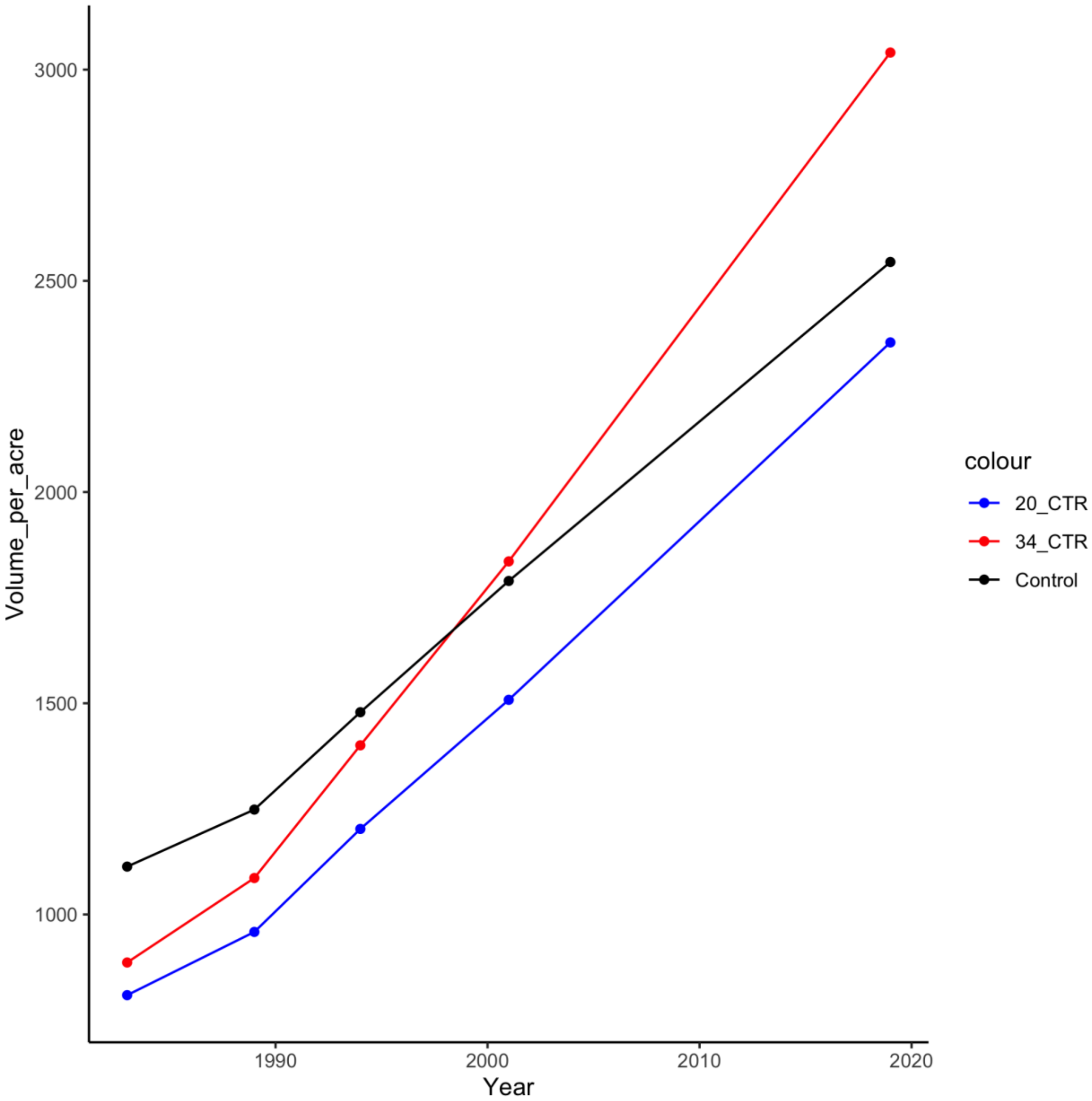


Table 6b. Butt-log Volume (board feet, Doyle) Per Acre of Crop-trees by Treatment over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	429.32	504.70	794.88	1099.11	1216.63	808.93	387.83
	1989	540.49	623.51	952.13	1287.24	1389.73	958.62	425.01
	1994	720.32	812.86	1228.03	1617.63	1633.46	1202.46	488.17
	2001	962.24	1069.36	1512.83	1951.60	2044.62	1508.13	553.29
	2019	1534.62	1765.41	2354.00	2942.85	3174.43	2354.26	789.11
34 CTR	1983	185.48	318.12	863.55	1431.67	1632.37	886.24	719.09
	1989	342.68	481.27	1066.95	1671.93	1868.45	1086.26	763.23
	1994	548.41	735.34	1396.89	2061.97	2259.48	1400.42	852.86
	2001	949.21	1060.30	1793.11	2568.66	2807.95	1835.85	949.21
	2019	1768.01	2079.81	3131.91	4092.56	4129.99	3040.46	1241.10
Control	1983	864.65	1086.08	1182.74	1209.93	1222.95	1113.27	167.87
	1989	968.26	1236.18	1331.97	1344.08	1360.95	1248.29	187.26
	1994	1140.47	1445.21	1549.48	1583.09	1675.85	1478.82	233.31
	2001	1374.46	1720.36	1845.50	1914.65	2092.58	1789.51	300.32
	2019	1987.16	2354.02	2485.89	2676.56	3219.82	2544.69	507.85

APPENDIX C: STAND FIGURES AND SUMMARY STATISTICS

Figure 1c. Trees Per Acre by Treatment over Time

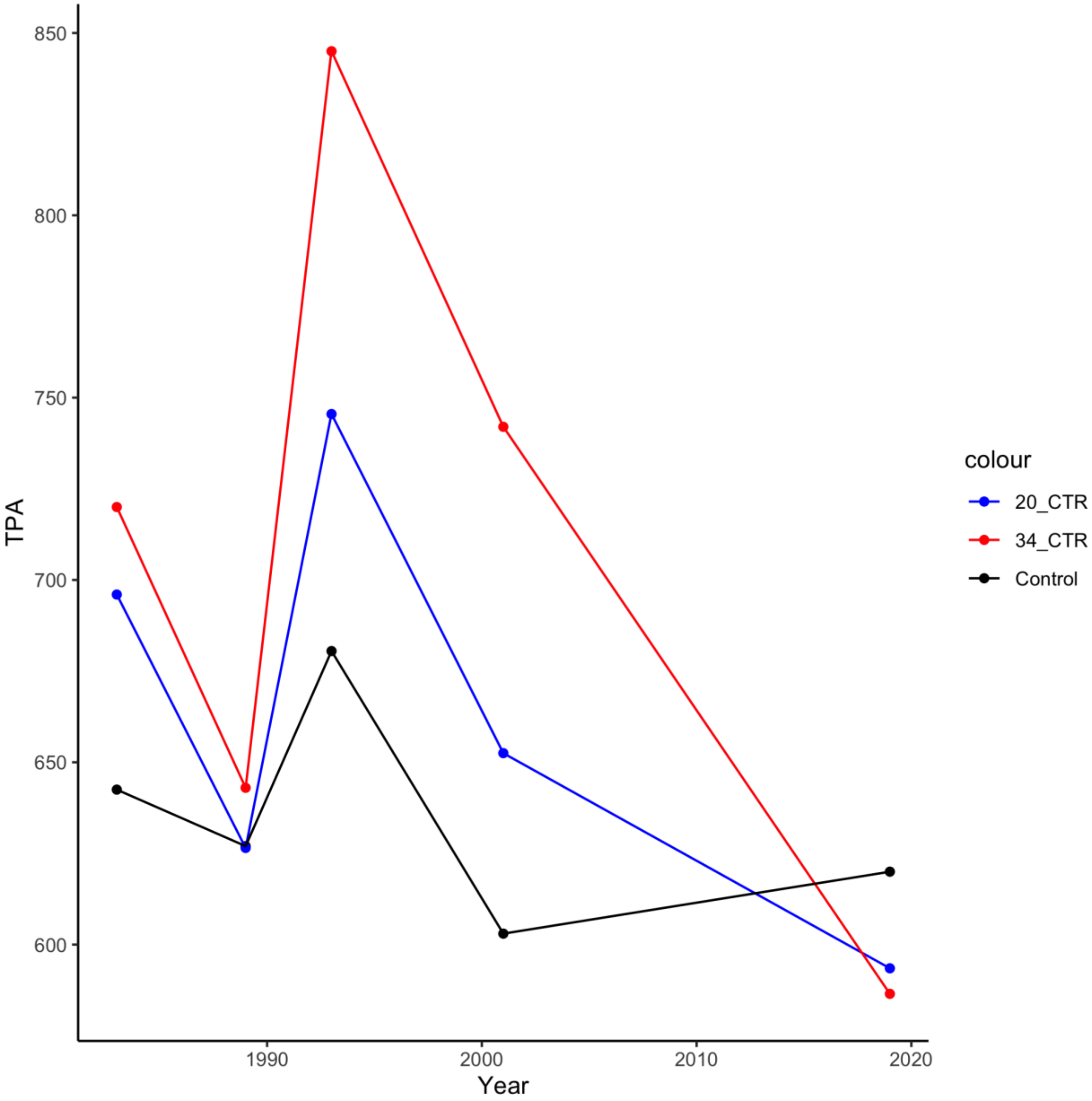


Table 1c. Trees Per Acre by Treatment over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	626	648.5	700	747.5	758	696	64.93
	1989	530	591.5	644	679	688	626.5	72.47
	1994	622	703	763	805.5	834	745.5	92.87
	2001	604	604	641	689.5	724	652.5	59.07
	2019	482	564.5	612	641	668	593.5	80.55
34 CTR	1983	666	685.5	711	745.5	792	720	54.72
	1989	572	590	643	696	714	643	69.52
	1994	644	824	888	909	960	845	138.27
	2001	636	726	766	782	800	742	72.92
	2019	476	536	589	639.5	692	586.5	92.25
Control	1983	422	581	686	747.5	776	642.5	158.78
	1989	418	526	651	752	788	627	169.90
	1994	468	549	672	803.5	910	680.5	196.98
	2001	448	557.5	599	644.5	766	603	129.97
	2019	446	563	620	677	794	620	142.83

Figure 2c. Cumulative Ingrowth (TPA) by Treatment Over Time

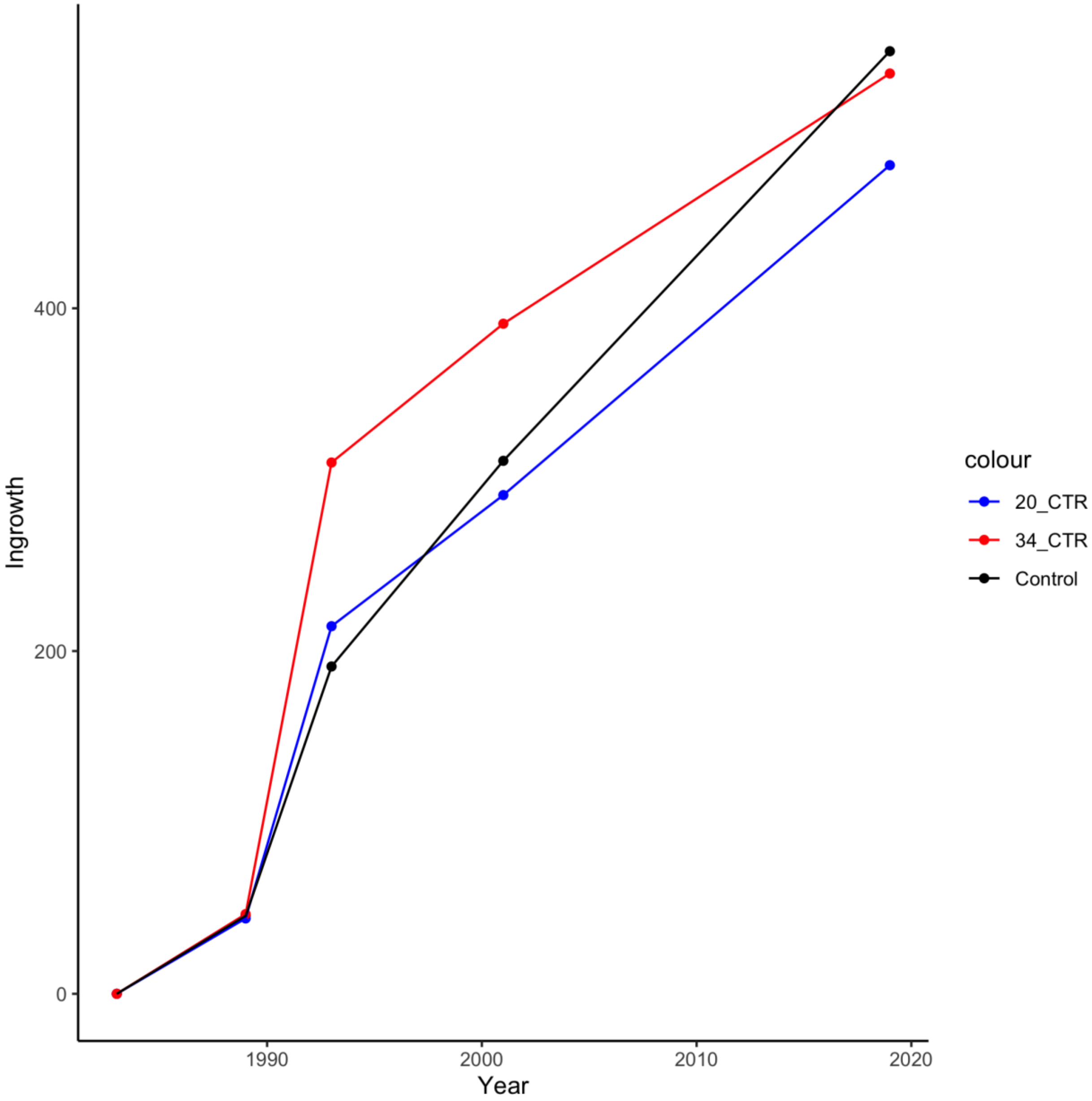


Table 2c. Cumulative Ingrowth (TPA) by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	0	0	0	0	0	0	0
	1989	12	36	47	55	70	44	24
	1994	150	150	204	269	300	215	76
	2001	212	242	281	330	390	291	77
	2019	338	467	516	533	564	484	100
34 CTR	1983	0	0	0	0	0	0	0
	1989	12	36	53	64	68	47	25
	1994	156	281	345	375	394	310	107
	2001	238	366	429	455	468	391	105
	2019	480	483	522	576	624	537	69
Control	1983	0	0	0	0	0	0	0
	1989	14	23	31	54	106	46	41
	1994	128	155	171	207	294	191	72
	2001	166	202	320	429	438	311	141
	2019	332	415	565	701	738	550	195

Figure 3c. Cumulative Mortality (TPA) by Treatment Over Time

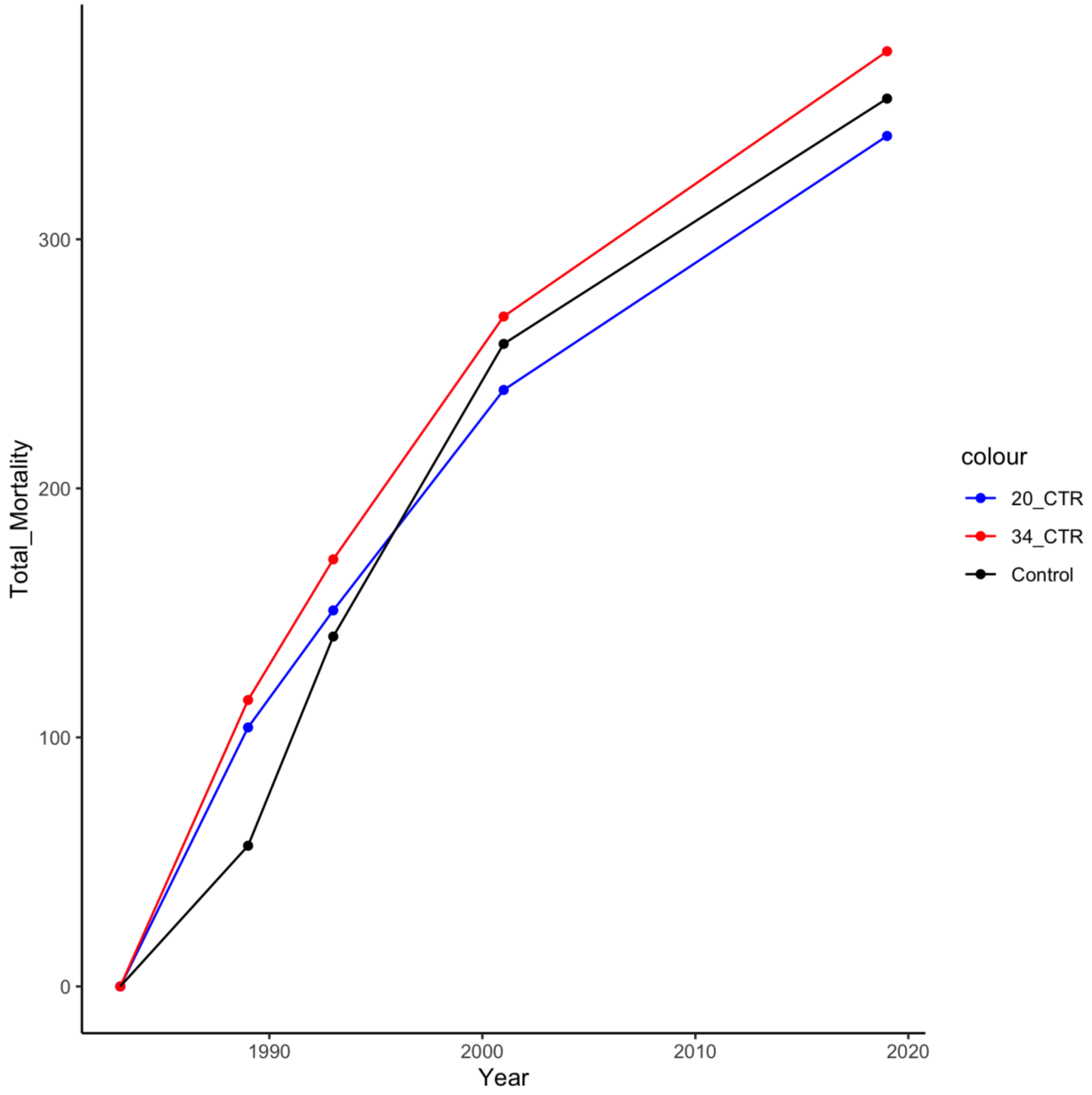


Table 3c. Cumulative Mortality (TPA) by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1989	92.00	101.00	105.00	108.00	114.00	104.00	9.09
	1994	138.00	144.00	150.00	157.00	166.00	151.00	11.94
	2001	202.00	217.00	238.00	260.50	280.00	239.50	34.46
	2019	292.00	319.00	342.00	364.50	390.00	341.50	41.61
34 CTR	1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1989	82.00	109.00	123.00	129.00	132.00	115.00	22.77
	1994	150.00	160.50	171.00	182.00	194.00	171.50	18.86
	2001	228.00	240.00	264.00	293.00	320.00	269.00	41.36
	2019	318.00	325.50	367.00	417.00	450.00	375.50	63.36
Control	1983	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1989	40.00	49.00	53.00	60.50	80.00	56.50	16.84
	1994	106.00	118.00	138.00	160.50	180.00	140.50	33.04
	2001	198.00	241.50	258.00	274.50	318.00	258.00	49.02
	2019	256.00	313.00	361.00	404.50	448.00	356.50	82.05

Figure 4c. Average Dbh (inches) by Treatment Over Time

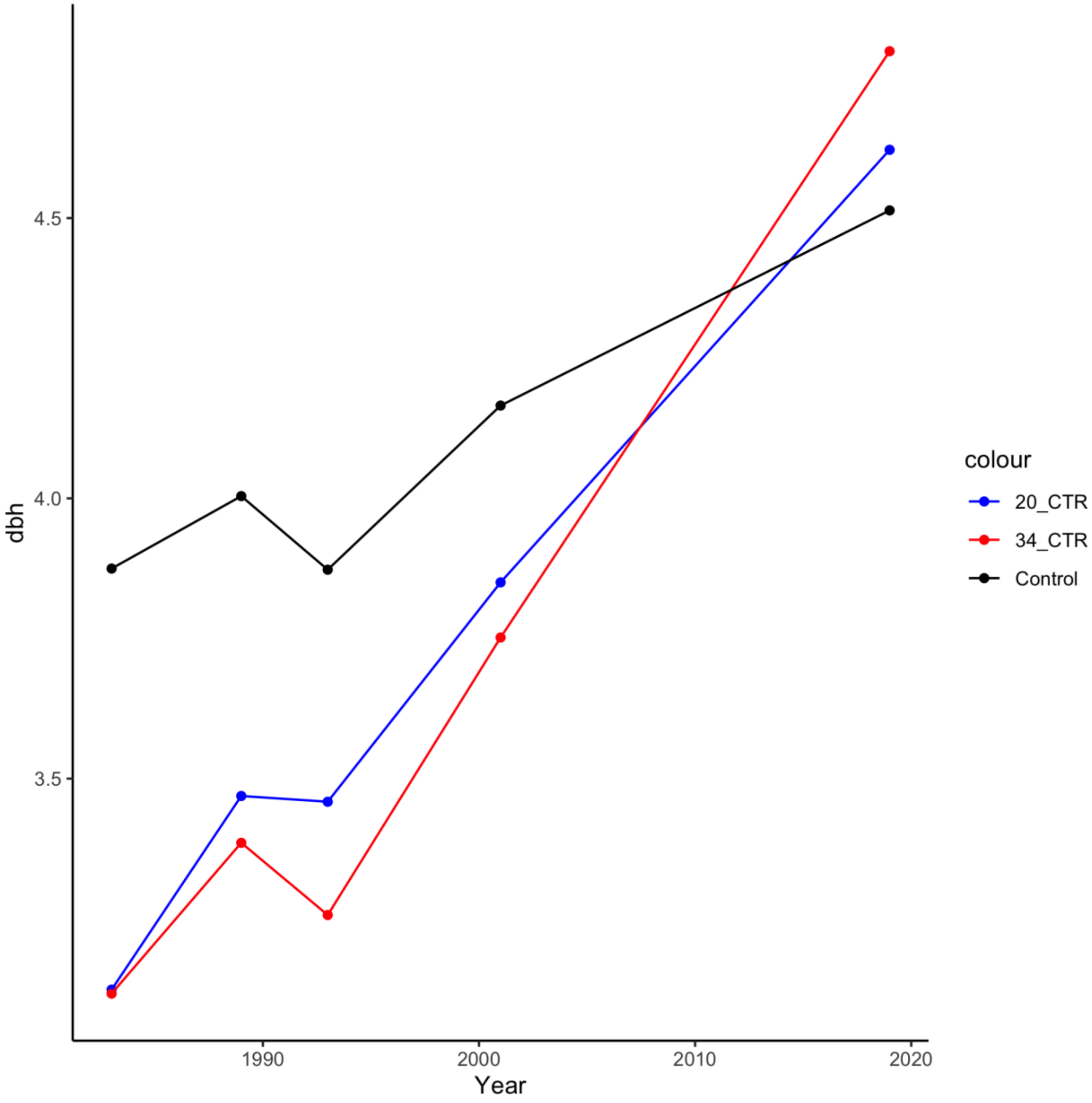


Table 4c. Average Dbh (inches) by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	2.82	3.02	3.12	3.22	3.43	3.12	0.25
	1989	3.26	3.33	3.35	3.49	3.92	3.47	0.30
	1994	3.26	3.33	3.42	3.54	3.73	3.46	0.20
	2001	3.75	3.80	3.85	3.90	3.96	3.85	0.09
	2019	4.11	4.39	4.52	4.75	5.35	4.62	0.52
34 CTR	1983	2.63	2.72	3.00	3.39	3.84	3.12	0.55
	1989	2.79	2.93	3.25	3.70	4.26	3.39	0.66
	1994	2.81	2.82	3.08	3.52	4.06	3.26	0.59
	2001	3.38	3.50	3.63	3.88	4.37	3.75	0.44
	2019	4.29	4.58	4.82	5.04	5.25	4.80	0.41
Control	1983	3.18	3.32	3.74	4.30	4.83	3.87	0.76
	1989	3.33	3.37	3.89	4.52	4.91	4.00	0.77
	1994	3.32	3.39	3.80	4.29	4.56	3.87	0.60
	2001	3.75	3.91	4.10	4.36	4.70	4.17	0.41
	2019	4.22	4.23	4.26	4.55	5.31	4.51	0.53

Figure 5c. Quadratic Mean Diameter (inches) by Treatment Over Time

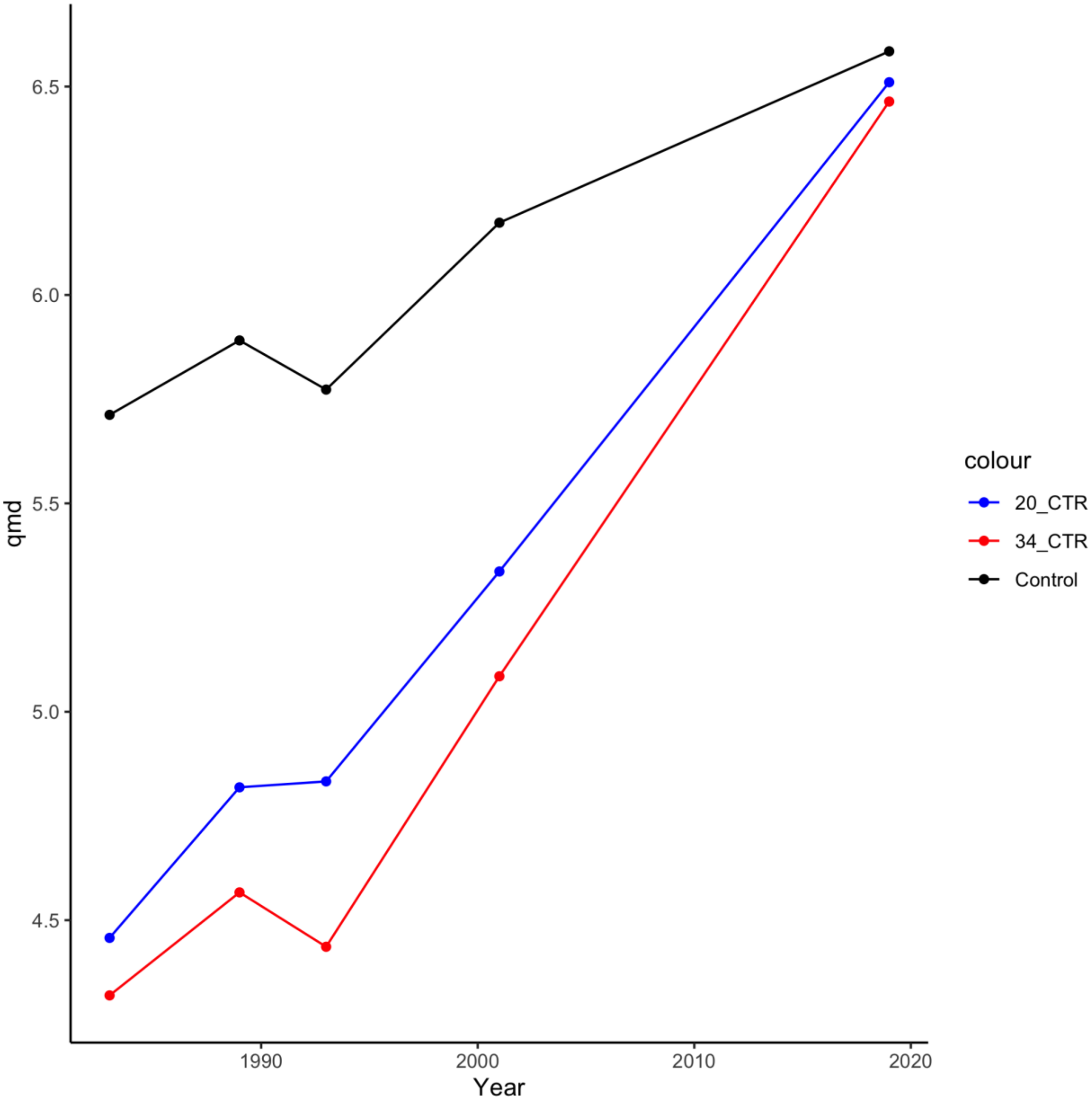


Table 5c. Quadratic Mean Diameter (inches) by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	4.18	4.42	4.54	4.57	4.58	4.46	0.19
	1989	4.66	4.70	4.74	4.86	5.12	4.82	0.21
	1994	4.59	4.73	4.86	4.96	5.03	4.83	0.19
	2001	5.15	5.27	5.33	5.40	5.53	5.34	0.15
	2019	5.78	6.12	6.44	6.83	7.39	6.51	0.68
34 CTR	1983	4.14	4.21	4.25	4.36	4.64	4.32	0.22
	1989	4.23	4.32	4.46	4.70	5.12	4.57	0.39
	1994	4.05	4.10	4.29	4.62	5.12	4.44	0.49
	2001	4.76	4.93	5.00	5.16	5.58	5.09	0.35
	2019	5.78	6.27	6.60	6.79	6.88	6.46	0.50
Control	1983	5.07	5.13	5.46	6.04	6.85	5.71	0.82
	1989	5.14	5.28	5.71	6.32	7.00	5.89	0.85
	1994	5.08	5.27	5.64	6.14	6.74	5.77	0.74
	2001	5.84	5.84	6.11	6.44	6.62	6.17	0.39
	2019	6.08	6.22	6.35	6.72	7.55	6.58	0.66

Figure 6c. Basal Area (ft2) Per Acre by Treatment Over Time

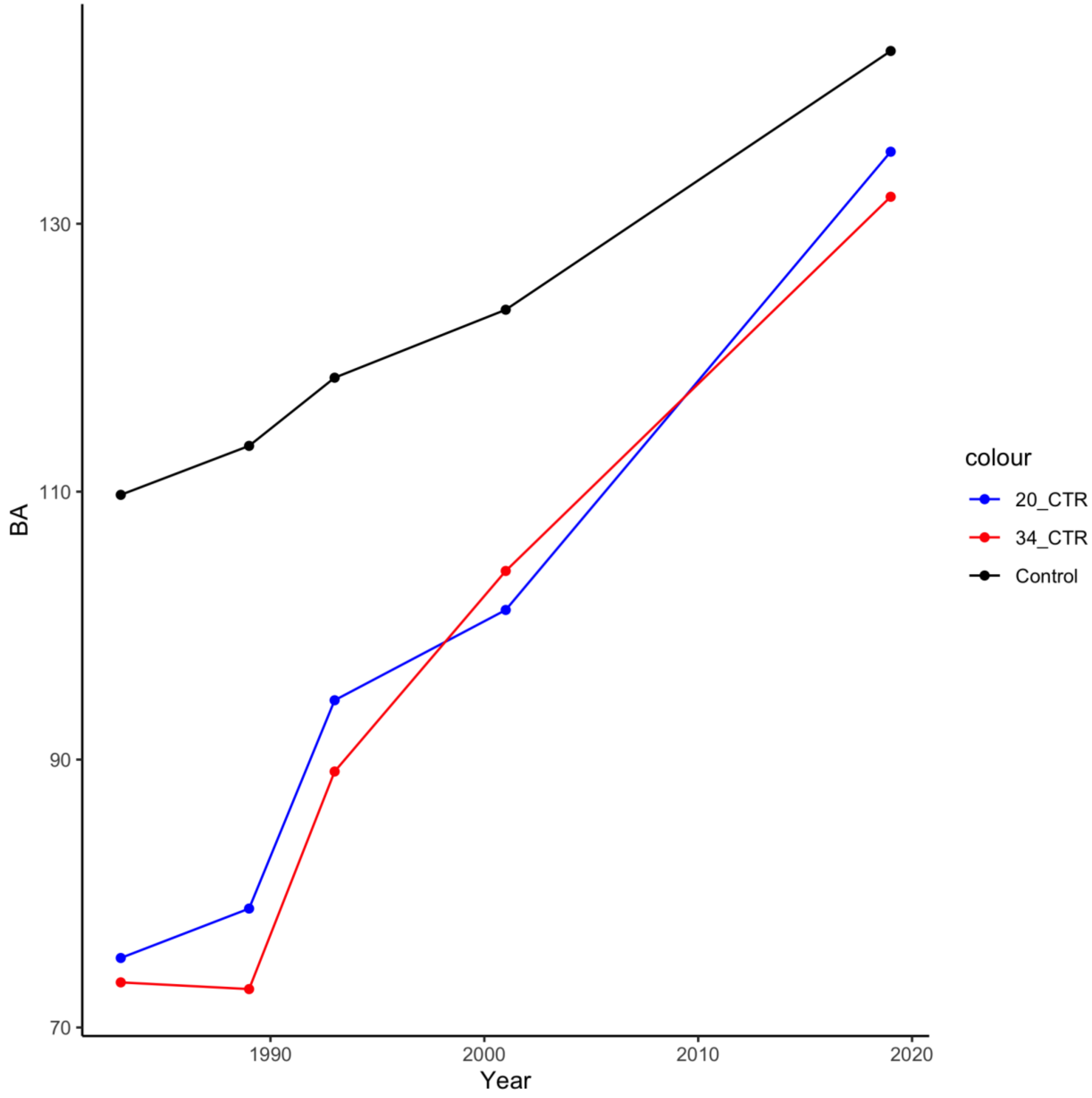


Table 6c. Basal Area (ft$_2$) Per Acre by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	71.64	72.01	73.46	76.63	82.20	75.19	4.87
	1989	75.81	76.04	78.87	81.71	81.96	78.88	3.37
	1994	85.79	93.39	96.41	97.44	99.10	94.43	5.91
	2001	94.55	97.28	99.42	103.31	111.30	101.17	7.20
	2019	121.65	130.73	138.22	142.86	143.43	135.38	10.15
34 CTR	1983	62.17	69.02	75.02	79.37	81.25	73.37	8.58
	1989	61.50	67.65	74.09	79.31	81.78	72.87	9.13
	1994	79.97	86.45	90.32	92.99	95.82	89.11	6.77
	2001	93.47	103.25	107.28	108.12	108.28	104.08	7.12
	2019	122.99	125.19	132.26	139.09	140.55	132.02	8.85
Control	1983	106.85	107.76	108.51	110.51	115.18	109.76	3.72
	1989	111.83	113.16	113.79	114.05	114.26	113.42	1.09
	1994	110.77	114.60	117.51	121.42	128.24	118.51	7.35
	2001	107.23	111.13	122.25	134.70	142.61	123.58	16.59
	2019	136.10	136.55	137.76	144.11	159.97	142.90	11.44

Figure 7c. Percent Stocking by Treatment Over Time

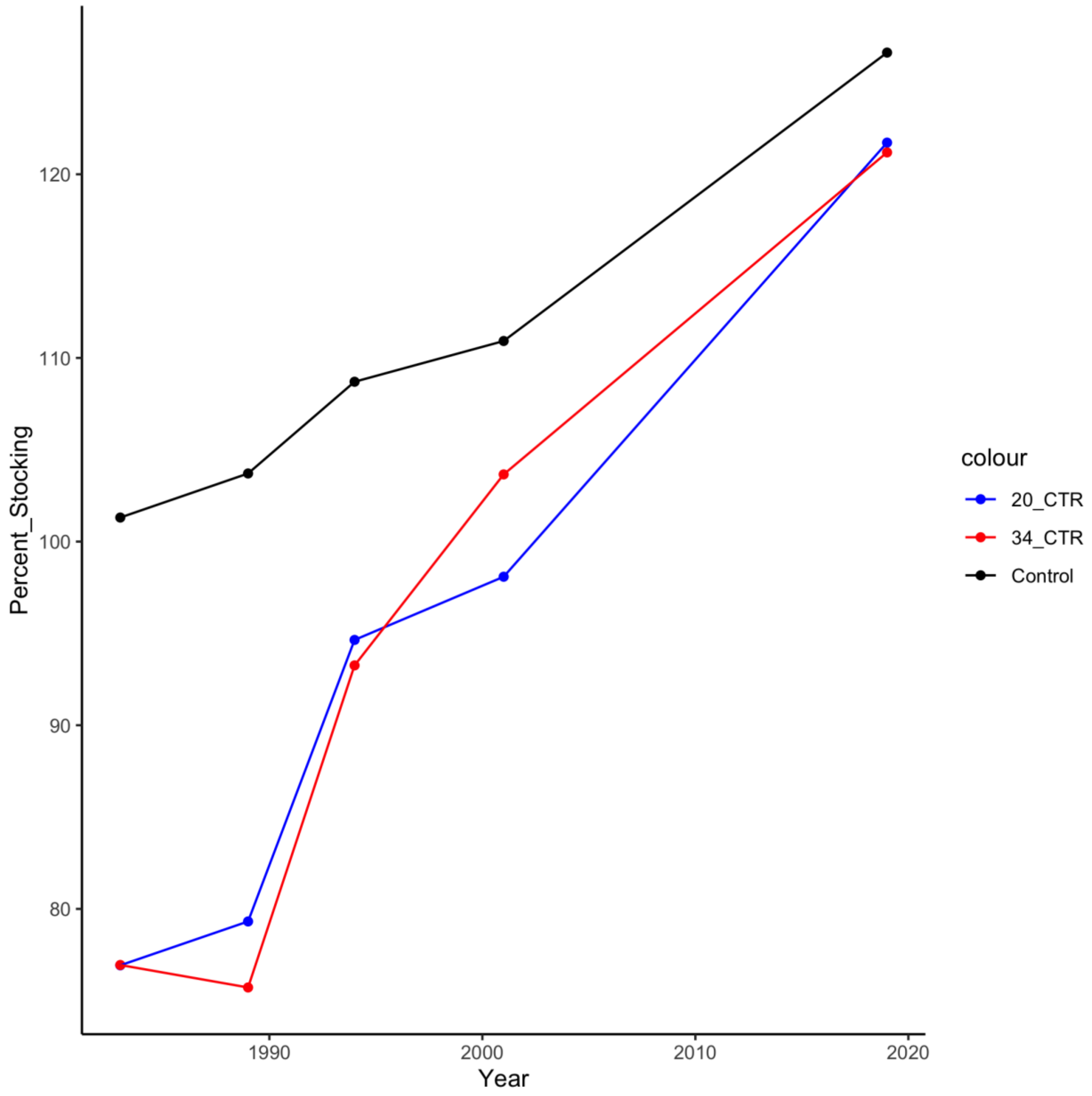


Table 7c. Percent Stocking by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	74.43	74.52	74.71	77.12	83.86	76.93	4.63
	1989	75.95	76.44	79.35	82.23	82.61	79.32	3.53
	1994	86.13	93.35	96.75	98.05	98.96	94.65	5.83
	2001	92.45	94.56	96.38	99.90	107.13	98.09	6.37
	2019	113.91	120.49	123.68	124.91	125.63	121.72	5.35
34 CTR	1983	63.84	73.80	77.53	80.67	88.88	76.95	10.25
	1989	62.82	68.76	77.05	84.01	85.96	75.72	10.87
	1994	84.45	90.56	93.61	96.31	101.37	93.26	6.97
	2001	93.88	101.88	105.69	107.46	109.37	103.66	6.81
	2019	109.35	117.43	123.71	127.47	127.99	121.19	8.66
Control	1983	95.26	99.19	100.91	103.03	108.16	101.31	5.30
	1989	97.70	103.35	105.25	105.61	106.64	103.71	4.06
	1994	101.22	102.19	106.16	112.68	121.26	108.70	9.19
	2001	95.81	99.53	108.68	120.07	130.52	110.92	15.79
	2019	118.61	119.64	120.98	127.96	145.94	126.63	12.95

Figure 8c. Butt-log Volume (board feet, Doyle) Per Tree by Treatment Over Time

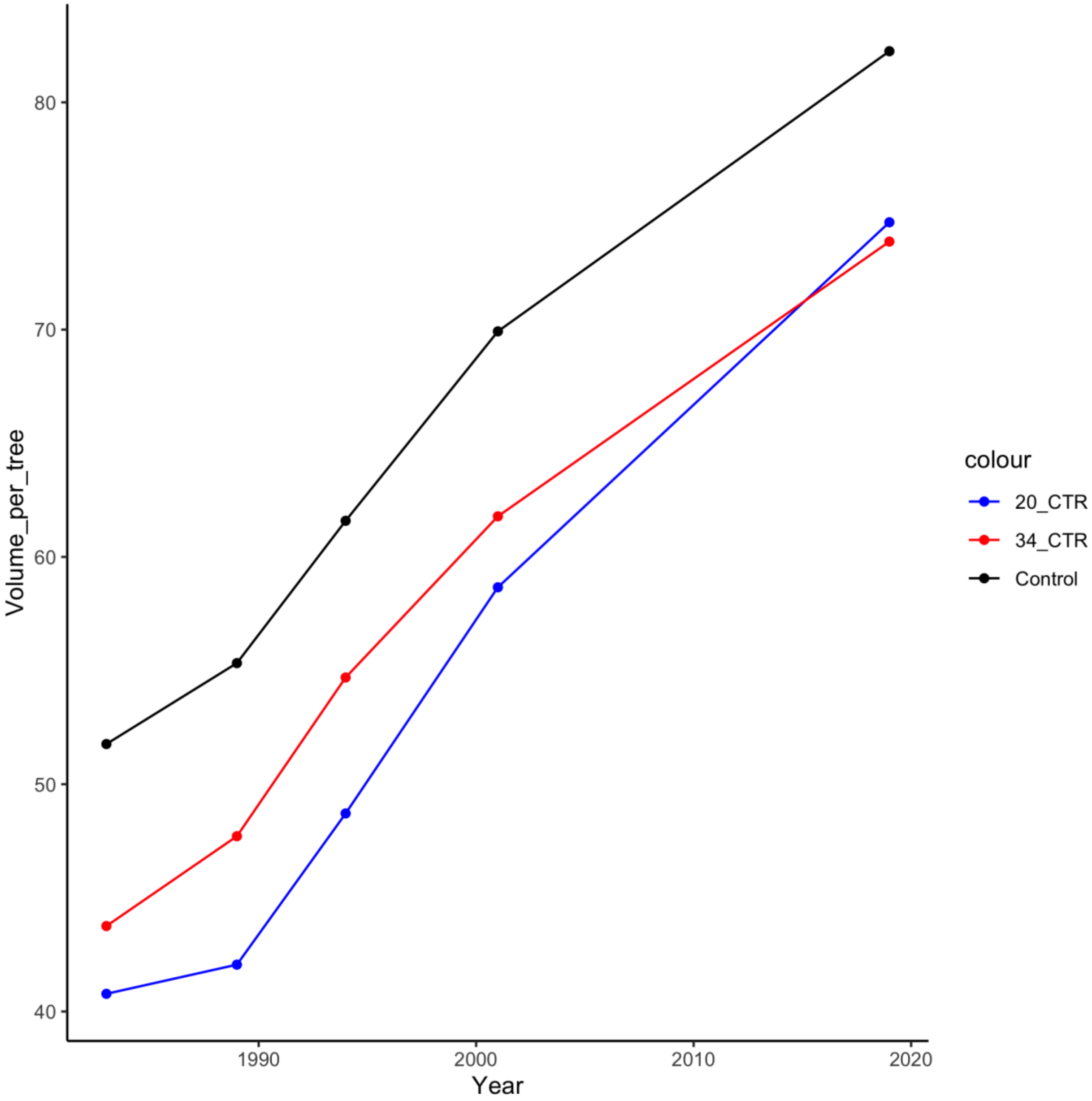


Table 8c. Butt-log Volume (board feet, Doyle) Per Tree by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	33.31	33.56	39.05	46.27	51.69	40.78	8.93
	1989	35.93	36.10	41.88	47.84	48.54	42.06	6.96
	1994	39.79	40.69	48.88	56.91	57.30	48.71	9.63
	2001	43.73	48.83	60.32	70.15	70.29	58.66	13.60
	2019	55.71	68.98	76.92	82.66	89.35	74.72	14.26
34 CTR	1983	32.41	34.43	44.03	53.36	54.57	43.76	11.62
	1989	29.85	39.16	47.71	56.26	65.58	47.71	15.25
	1994	33.90	47.74	53.31	60.27	78.26	54.70	18.20
	2001	39.08	51.96	58.12	67.95	91.82	61.79	21.99
	2019	47.01	55.33	73.87	92.42	100.74	73.87	25.44
Control	1983	47.23	47.41	50.23	54.58	59.38	51.77	5.73
	1989	51.38	51.67	54.67	58.33	60.58	55.33	4.51
	1994	54.76	56.76	61.50	66.34	68.59	61.59	6.56
	2001	63.97	67.55	69.20	71.57	77.33	69.92	5.53
	2019	69.78	79.74	83.07	85.58	93.08	82.25	9.56

Figure 9c. Butt-log Volume (board feet, Doyle) Per Acre by Treatment Over Time

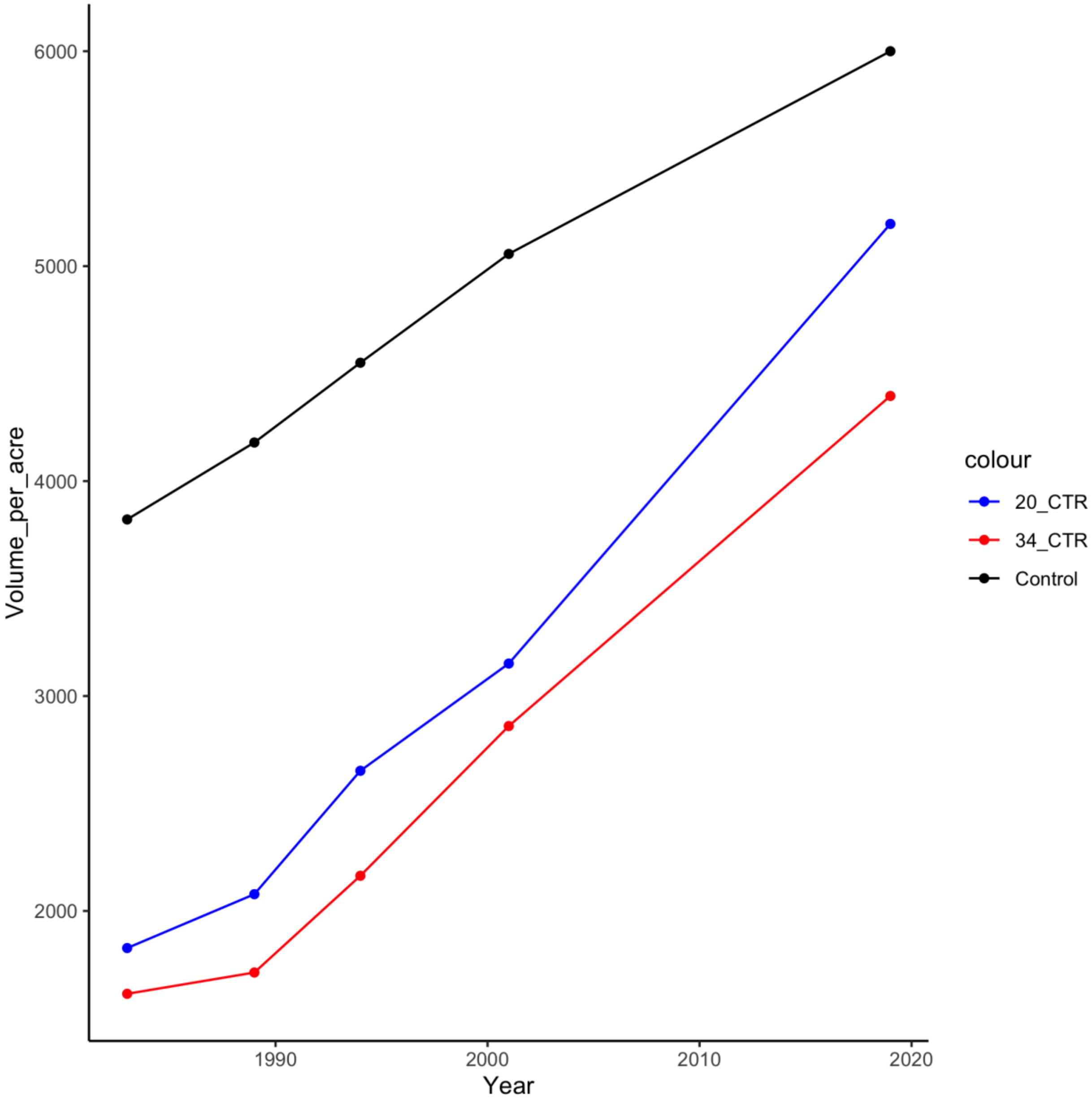


Table 9c. Butt-log Volume (board feet, Doyle) Per Acre by Treatment Over Time

Treatment	Year	Min	1st Quartile	Median	3rd Quartile	Max	Mean	SD
20 CTR	1983	1345.63	1735.58	1914.85	2006.72	2134.49	1827.45	339.88
	1989	1591.02	1906.99	2122.65	2293.66	2475.64	2077.99	375.77
	1994	1989.72	2341.75	2762.49	3072.97	3094.20	2652.23	529.99
	2001	2536.48	2604.75	3141.29	3687.68	3785.54	3151.15	660.40
	2019	3899.81	4498.18	5386.75	6085.09	6112.78	5196.52	1086.76
34 CTR	1983	713.02	1078.67	1442.62	1978.47	2859.83	1614.52	920.11
	1989	1014.85	1370.02	1673.92	2017.61	2492.13	1713.71	623.52
	1994	1423.89	1821.21	2128.63	2471.15	2973.77	2163.73	649.93
	2001	2188.50	2572.41	2789.94	3077.78	3672.66	2860.26	615.68
	2019	3290.52	4134.35	4628.31	4890.02	5037.07	4396.05	781.34
Control	1983	3513.23	3570.47	3808.24	4059.27	4156.33	3821.51	317.88
	1989	3699.64	3953.30	4207.01	4433.15	4604.10	4179.44	395.51
	1994	3833.31	4489.68	4715.28	4776.25	4938.72	4550.65	489.72
	2001	4124.87	4478.77	5113.01	5691.21	5877.01	5056.97	832.79
	2019	5582.44	5863.50	6051.70	6188.17	6314.03	5999.97	314.21

APPENDIX D: ANOVA TABLES

Table 1d. Type III Anova for Avg. Dbh of Crop-trees

Parameter	Df	Sum Sq	F value	P value
Treatment	2	57.300	7.097	0.002
Year	4	226.600	14.038	<0.001
Treatment:Year	8	3.200	0.100	0.999
Residuals	45	181.600		

Table 2d. Tukey Pairwise Comparisons of Avg. Dbh of Crop-trees among Treatments

Contrast	Estimate	SE	Df	T ratio	P value
20CTR – 34 CTR	2.120	0.635	45	3.338	0.005
20 CTR – Control	0.100	0.635	45	0.157	0.987
34 CTR - Control	-2.021	0.635	45	-3.182	0.007

Table 3d. Tukey Pairwise Comparisons of Avg. Dbh of Crop-trees among Years

Contrast	Estimate	SE	Df	T ratio	P value
1983 – 1989	-0.673	0.82	45	-0.821	0.923
1983 – 1994	-1.672	0.82	45	-2.039	0.265
1983 – 2001	-2.869	0.82	45	-3.499	0.009
1983 – 2019	-5.516	0.82	45	-6.727	<0.001
1989 – 1994	-0.999	0.82	45	-1.218	0.741
1989 – 2001	-2.196	0.82	45	-2.678	0.073
1989 – 2019	-4.843	0.82	45	-5.906	<0.001
1994 – 2001	-1.197	0.82	45	-1.460	0.593
1994 – 2019	-3.844	0.82	45	-4.688	<0.001
2001 – 2019	-2.647	0.82	45	-3.228	0.019

Table 4d. Type III Anova for PAI Dbh of Crop-trees

Parameter	Df	Sum Sq	F value	P value
Treatment	2	0.019	14.399	<0.001
Period	3	0.030	14.788	<0.001
Treatment:Period	6	0.001	0.211	0.971
Residuals	36	0.024		

Table 5d. Tukey Pairwise Comparisons of PAI Dbh of Crop-trees among Treatments

Contrast	Estimate	SE	Df	T ratio	P value
20CTR – 34 CTR	0.020	0.009	36	2.204	0.084
20 CTR – Control	0.049	0.009	36	5.399	<0.001
34 CTR - Control	0.029	0.009	36	3.135	0.009

Table 6d. Tukey Pairwise Comparisons of PAI Dbh of Crop-trees among Periods

Contrast	Estimate	SE	Df	T ratio	P value
1983 to 1989 – 1989 to 1994	-0.065	0.011	36	-6.166	<0.001
1983 to 1989 – 1994 to 2001	-0.036	0.011	36	-3.442	0.008
1983 to 1989 – 2001 to 2019	-0.012	0.011	36	-1.174	0.647
1994 to 2001 – 1989 to 1994	-0.029	0.011	36	-2.724	0.047
1994 to 2001 – 2001 to 2019	0.024	0.011	36	2.268	0.125
2001 to 2019 – 1989 to 1994	-0.053	0.011	36	-4.992	<0.001

Table 7d. Type III Anova for MaxPG of Crop-trees

Parameter	Df	Chi square	P value
Treatment	2	34.073	<0.001
Year	4	25.393	<0.001
Treatment:Year	8	13.342	0.101

Table 8d. Tukey Pairwise Comparisons of MaxPG of Crop-trees among Treatments

Estimates are given on the logs odds ratio scale.

Contrast	Estimate	SE	Z ratio	P value
20CTR – 34 CTR	0.184	0.293	0.626	0.806
20 CTR – Control	1.209	0.294	4.114	<0.001
34 CTR - Control	1.026	0.198	5.173	<0.001

Table 9d. Tukey Pairwise Comparisons of MaxPG of Crop-trees among Years. Estimates are given on the logs odds ratio scale.

Contrast	Estimate	SE	Z ratio	P value
1983 – 1989	0.761	0.281	2.704	0.053
1983 – 1994	0.585	0.285	2.054	0.241
1983 – 2001	0.074	0.297	0.250	0.999
1983 – 2019	-0.741	0.429	-1.727	0.417
1989 – 1994	-0.176	0.261	-0.673	0.962
1989 – 2001	-0.687	0.274	-2.510	0.088
1989 – 2019	-1.502	0.413	-3.635	0.003
1994 – 2001	-0.511	0.277	-1.843	0.349
1994 – 2019	-1.326	0.416	-3.191	0.012
2001 – 2019	-0.815	0.424	-1.923	0.305

Table 10d. Type III Anova for Mean Butt-log Value of Crop-trees

Parameter	Df	Sum Sq	F value	P value
Treatment	2	6854	0.723	0.511
Residuals	9	42652		

Table 11d. Type III Anova for Stand NPV Per Acre

Parameter	Df	Sum Sq	F value	P value
Treatment	2	222352	0.052	0.950
Residuals	9	19401220		

Table 12d. Type III Anova for Stand BA Per Acre

Parameter	Df	Sum Sq	F value	P value
Treatment	2	9154	69.317	<0.001
Year	4	20090	76.064	<0.001
Treatment:Year	8	1505	2.850	0.012
Residuals	45	2971		

Table 13d. Tukey Pairwise Comparisons of Stand BA Per Acre among Treatments in Year 1983

Contrast	Estimate	SE	Df	T ratio	P value
20 CTR – 34 CTR	1.82	5.75	45	0.317	0.946
20 CTR - Control	-34.58	5.75	45	-6.017	<0.001
34 CTR - Control	-36.40	5.75	45	-6.334	<0.001

Table 14d. Tukey Pairwise Comparisons of Stand BA Per Acre among Treatments in Year 1989

Contrast	Estimate	SE	Df	T ratio	P value
20 CTR – 34 CTR	6.14	5.75	45	1.069	0.538
20 CTR - Control	-34.55	5.75	45	-6.013	<0.001

34 CTR - Control	-40.69	5.75	45	-7.082	<0.001

Table 15d. Tukey Pairwise Comparisons of Stand BA Per Acre among Treatments in Year 1994

Contrast	Estimate	SE	Df	T ratio	P value
20 CTR – 34 CTR	6.19	5.75	45	1.077	0.533
20 CTR - Control	-23.85	5.75	45	-4.150	<0.001
34 CTR - Control	-30.03	5.75	45	-5.227	<0.001

Table 16d. Tukey Pairwise Comparisons of Stand BA Per Acre among Treatments in Year 2001

Contrast	Estimate	SE	Df	T ratio	P value
20 CTR – 34 CTR	-2.23	5.75	45	-0.287	0.921
20 CTR - Control	-22.03	5.75	45	-3.834	0.001
34 CTR - Control	-19.80	5.75	45	-3.446	0.004

Table 17d. Tukey Pairwise Comparisons of Stand BA Per Acre among Treatments in Year 2019

Contrast	Estimate	SE	Df	T ratio	P value
20 CTR – 34 CTR	3.34	5.75	45	0.581	0.831
20 CTR - Control	-7.71	5.75	45	-1.342	0.380
34 CTR - Control	-11.05	5.75	45	-1.923	0.144

Table 18d. Tukey Pairwise Comparisons of Stand BA Per Acre among Years for the 20 CTR Treatment

Contrast	Estimate	SE	Df	T ratio	P value
1983 – 1989	-3.488	5.75	45	-0.626	0.973
1983 – 1994	-17.820	5.75	45	-3.101	0.026
1983 – 2001	-24.238	5.75	45	-4.218	0.001
1983 – 2019	-59.997	5.75	45	-10.442	<0.001
1989 – 1994	-14.332	5.75	45	-2.494	0.110
1989 – 2001	-20.750	5.75	45	-3.611	0.007
1989 – 2019	-56.510	5.75	45	-9.835	<0.001
1994 – 2001	-6.418	5.75	45	-1.117	0.797
1994 – 2019	-42.177	5.75	45	-7.340	<0.001
2001 – 2019	-35.759	5.75	45	-6.223	<0.001

Table 19d. Tukey Pairwise Comparisons of Stand BA Per Acre among Years for the 34 CTR Treatment

Contrast	Estimate	SE	Df	T ratio	P value
1983 – 1989	0.834	5.75	45	0.145	1.000
1983 – 1994	-13.453	5.75	45	-2.341	0.151
1983 – 2001	-28.284	5.75	45	-4.922	<0.001
1983 – 2019	-58.483	5.75	45	-10.178	<0.001
1989 – 1994	-14.287	5.75	45	-2.487	0.111
1989 – 2001	-29.118	5.75	45	-5.068	<0.001
1989 – 2019	-59.316	5.75	45	-10.323	<0.001
1994 – 2001	-14.831	5.75	45	-2.581	0.091
1994 – 2019	-45.029	5.75	45	-7.837	<0.001
2001 – 2019	-30.199	5.75	45	-5.256	<0.001

Table 20d. Tukey Pairwise Comparisons of Stand BA Per Acre among Years for the Control Treatment

Contrast	Estimate	SE	Df	T ratio	P value
1983 – 1989	-3.462	5.75	45	-0.602	0.974
1983 – 1994	-7.091	5.75	45	-1.234	0.732
1983 – 2001	-11.691	5.75	45	-2.035	0.267
1983 – 2019	-33.136	5.75	45	-5.767	<0.001
1989 – 1994	-3.630	5.75	45	-0.632	0.969
1989 – 2001	-8.229	5.75	45	-1.432	0.611
1989 – 2019	-29.674	5.75	45	-5.164	<0.001
1994 – 2001	-4.600	5.75	45	-0.800	0.929
1994 – 2019	-26.045	5.75	45	-4.533	<0.001
2001 – 2019	-21.445	5.75	45	-3.732	0.005

Table 21d. Type III Anova for Stand Percent Stocking

Parameter	Df	Sum Sq	F value	P value
Treatment	2	3636	26.040	<0.001
Year	4	11503	41.195	<0.001
Treatment:Year	8	921	1.649	0.138
Residuals	45	3141		

Table 22d. Tukey Pairwise Comparisons of Percent Stocking among Treatments

Contrast	Estimate	SE	Df	T ratio	P value
20CTR – 34 CTR	0.61	2.64	45	0.231	0.971
20 CTR – Control	-16.20	2.64	45	-6.131	<0.001
34 CTR - Control	-16.81	2.64	45	-6.362	<0.001

Table 23d. Tukey Pairwise Comparisons of Percent Stocking among Years

Contrast	Estimate	SE	Df	T ratio	P value
1983 – 1989	-0.644	3.41	45	-0.189	1.000
1983 – 1994	-10.345	3.41	45	-3.033	0.031
1983 – 2001	-15.412	3.41	45	-4.518	<0.001
1983 – 2019	-37.982	3.41	45	-11.135	<0.001
1989 – 1994	-9.701	3.41	45	-2.844	0.050
1989 – 2001	-14.768	3.41	45	-4.330	<0.001
1989 – 2019	-37.339	3.41	45	-10.947	<0.001
1994 – 2001	-5.067	3.41	45	-1.486	0.577
1994 – 2019	-27.638	3.41	45	-8.103	<0.001
2001 – 2019	-22.570	3.41	45	-6.617	<0.001

Table 24d. Type III Anova for Stand Ingrowth Per Acre

Parameter	Df	Sum Sq	F value	P value
Treatment	2	14333	0.687	0.528
Residuals	9	93922		

APPENDIX E: R CODE

```
## Title: CTR Master Code
# Author: Philip Vogel
# Created: April 22, 2020

pkgs <- c("nlme", "car", "lme4", "emmeans", "ggplot2", "tidyverse")

for(i in 1:length(pkgs)) {
  if(pkgs[i] %in% installed.packages()) {
    require(pkgs[i], character.only = T)
  } else {
    install.packages(pkgs[i])
    require(pkgs[i], character.only = T)
  }
}

# Import CSV -----------------------------------------------------------
----

#import ctr_full csv
ctr <- read_csv("ctr_full.csv",
                col_types = cols(
                  Order=col_double(),
                  Plot=col_factor(),
                  Treatment=col_factor(),
                  ID=col_double(),
                  Species.Name=col_character(),
                  Cropcut=col_factor(),
                  Classification=col_character(),
                  Damage=col_factor(),
                  Severity=col_factor(),
                  CC0=col_double(),
                  CC5=col_double(),
                  CC10=col_double(),
                  CC17=col_double(),
                  CC35=col_double(),
                  PREDBH=col_double(),
                  DBH0=col_double(),
                  DBH5=col_double(),
                  DBH10=col_double(),
                  DBH17=col_double(),
                  DBH35=col_double(),
                  G0=col_double(),
                  G5=col_double(),
                  G10=col_double(),
                  G17=col_double(),
                  G35=col_double(),
                  MORT0=col_double(),
                  MORT5=col_double(),
                  MORT10=col_double(),
                  MORT17=col_double(),
                  MORT35=col_double(),
                  STEMS0=col_double(),
                  STEMS5=col_double(),
                  STEMS10=col_double(),
                  STEMS17=col_double(),
                  STEMS35=col_double(),
                  REMARKS0=col_character(),
```

```
                  REMARKS5=col_character(),
                  REMARKS10=col_character(),
                  REMARKS17=col_character(),
                  REMARKS35=col_character()
                ))

#rename treatment factors
ctr$Treatment <- ifelse(ctr$Treatment==1, "20_CTR",
                             ifelse(ctr$Treatment==2, "34_CTR",
"Control"))

#import si.age csv
SI.AGE <- read_csv("si_age.csv",
                   col_types=cols(
                     Plot=col_factor()
                   ))


# Load CTR Functions ####
mesavage = function( dbh, mht, volumetype="Int1/4", girard=78)
{
  # Function to calcalate the Mesavage and Girard 1946 volume.
  # using the equations by H.V. Wiant, Jr., 1986, Formula's for
  # Mesavage and Girard's Volume Tables, Northern Journal of Applied
Forestry 3:124.
  # Coded by David R. Larsen, June 20, 2015

  L = mht / 16.0
  cor = (1.0+ ((girard - 78.0) * 0.03))
  a = vector()
  b = vector()
  c = vector()
  treevolume=numeric()

  if (volumetype == "Int1/4"){
    a = c(-13.35212, 9.58615, 1.52968)
    b = c(1.79620, -2.59995, -0.27465)
    c = c(0.04482, 0.45997, -0.00961)
  }else if (volumetype == "Scribner"){
    a = c(-22.50365, 17.53508, -0.59242)
    b = c(3.02888, -4.34381, -0.02302)
    c = c(-0.01969, 0.51593, -0.02035)
  }else if (volumetype == "Doyle"){
    a = c(-29.37337, 41.51275, 0.55743)
    b = c(2.78043, -8.77272, -0.04516)
    c = c(0.04177, 0.59042,  -0.01578)
  }else{
    cat("volumetype not found!")
  }

  v1 = (a[1] + a[2] * L + a[3] * L**2)
  v2 = (b[1] + b[2] * L + b[3] * L**2) * dbh
  v3 = (c[1] + c[2] * L + c[3] * L**2) * dbh**2
  volume = (v1 + v2 + v3) * cor
  volume
}
```

```
#function for basal area per acre using dbh
#the total sum of the constant k multiplied by the square of the dbh of
one tree divided by 1/2 (acreage)
ba = function( dia, weight)
{
  ba=0.005454154*dia^2*weight
  batot=sum(ba, na.rm=TRUE)
  batot
}

#function for trees per acre using number of trees
#the number of trees multiplied by the expansion factor (2)
#while it is possible to simply create a TPA column (which I do in
section: Calculate % Stocking),
#a function for calculating TPA is convenient for creating summaries
#Additionally, it avoids extraneous columns (e.g. a column of 2's and
NA's)
tpa<-function(n, weight, na.rm)
{
  if (na.rm) n<-na.omit(n)
  tpa=length(n)*weight
  tpa
}

percent.stocking = function(tpa, dbh, b = c(-0.00507, 0.01698,
0.00317), adj=1 )
{
  percent <- ((b[1]*tpa+b[2]*(tpa*dbh)+b[3]*(tpa*(dbh^2))))
  percenttot=sum(percent, na.rm=TRUE)
  percenttot
}


qmd = function( ba, tpa, unittype="imperial" )
{
  # Function to calculate the quadratic mean diameter from basal area
and tree per acre
  # by David R. Larsen, Copyright October 9, 2012
  # Creative Commons http://creativecommons.org/licenses/by-nc/3.0/us/

  if (unittype == "imperial"){
    qmd = sqrt((ba / tpa) / 0.005454154)
  }else if (unitype == "metric"){
    qmd = sqrt((ba / tpa) / 0.00007854)
  }else{
    qmd = 0
  }
  qmd
}

#function for standard error
stderr <- function(x, na.rm=FALSE)
{
  if (na.rm) x <- na.omit(x)
  (sd(x))/(sqrt(length(x)))
}
```

```
bal <- function(dia, weight)
{
  ba=0.005454154*dia^2*weight
  batot=sum(ba, na.rm=TRUE)
  basmaller <- 0
  pix <- 0
  bal <- 0
  for (i in 1 : length(ba)) {
    bax<-ba[i]
    basmaller <- sum(ba[ba<=bax], na.rm=TRUE)
    pix <- basmaller/batot
    bal[i] <- batot*(1-pix)
  }
  return(bal)
}

# Create recruitment column ####
ctr <- ctr%>%
  mutate(
    REC0 = NA,
    REC5 = ifelse(is.na(DBH0) & !is.na(DBH5), 1, 0),
    REC10 = ifelse(is.na(DBH0) & is.na(DBH5) & !is.na(DBH10), 1, 0),
    REC17 = ifelse(is.na(DBH0) & is.na(DBH5) & is.na(DBH10) &
!is.na(DBH17), 1, 0),
    REC35 = ifelse(is.na(DBH0) & is.na(DBH5) & is.na(DBH10) &
is.na(DBH17) & !is.na(DBH35), 1, 0)
  )

# Create ingrowth category ####
ctr <- ctr%>%
  mutate(
    Classification = ifelse(REC5 == 1 |
                              REC10 == 1 |
                              REC17 == 1 |
                              REC35 == 1, "ingrowth", Classification),
    Classification = ifelse(Classification == "ingrowth" &
is.na(PREDBH) & DBH35 > 12, "non-crop-tree", Classification)
  )
# Calculate Butt-log Volume (VOL) using mesavage function ####

ctr <- ctr%>%
  mutate(
    VOL0 = ifelse(DBH0 >= 9.6,
                  mesavage(DBH0, 16, "Doyle", 78), NA),
    VOL5 = ifelse(DBH5 >= 9.6,
                  mesavage(DBH5, 16, "Doyle", 78), NA),
    VOL10 = ifelse(DBH10 >= 9.6,
                  mesavage(DBH10, 16, "Doyle", 78), NA),
    VOL17 = ifelse(DBH17 >= 9.6,
                  mesavage(DBH17, 16, "Doyle", 78), NA),
    VOL35 = ifelse(DBH35 >= 9.6,
                  mesavage(DBH35, 16, "Doyle", 78), NA))

# Calculate quality variables -----------------------------------------
----
```

```
#Calculate the grade change "GDELTA35", $ value of tree "VALUE35",
maximum potential grade "GMAX",
#and the difference between maximum potential grade and realized grade
"GDIFF"
#Also, create a factor column "GFACT" where 1 indicates that a tree has
realized its maximum potential grade
#and 0 indicated that a tree has not reached its max potential grade

ctr <- ctr%>%
  mutate(
    STUMPAGE0 = ifelse(G0 == 1, 507,
                        ifelse(G0 == 2, 276.625,
                               ifelse(G0 == 3, 159.625,
                                      ifelse(G0 == 4, 0, NA)))),
    STUMPAGE5 = ifelse(G5 == 1, 507,
                       ifelse(G5 == 2, 276.625,
                              ifelse(G5 == 3, 159.625,
                                     ifelse(G5 == 4, 0, NA)))),
    STUMPAGE10 = ifelse(G10 == 1, 507,
                       ifelse(G10 == 2, 276.625,
                              ifelse(G10 == 3, 159.625,
                                     ifelse(G10 == 4, 0, NA)))),
    STUMPAGE17 = ifelse(G17 == 1, 507,
                       ifelse(G17 == 2, 276.625,
                              ifelse(G17 == 3, 159.625,
                                     ifelse(G17 == 4, 0, NA)))),
    STUMPAGE35.2 = ifelse(G35 == 1, 507,
                          ifelse(G35 == 2, 276.625,
                                 ifelse(G35 == 3, 159.625,
                                        ifelse(G35 == 4, 0, NA)))),
    VALUE0 = ((VOL0)*(STUMPAGE0/1000)),
    VALUE5 = ((VOL5)*(STUMPAGE5/1000)),
    VALUE10 = ((VOL10)*(STUMPAGE10/1000)),
    VALUE17 = ((VOL17)*(STUMPAGE17/1000)),
    VALUE35.2 = ((VOL35)*(STUMPAGE35.2/1000)),
    VALUE35 = ((VOL35)*(STUMPAGE35/1000)), #Stumpage values reflect
1000 bdft #using butt-log bdft
    GMAX0 = ifelse(DBH0 >= 9.6 & DBH0 < 12.6, 3,
                   ifelse(DBH0 >= 12.6 & DBH0 <15.6, 2,
                          ifelse(DBH0 >=15.6, 1, 4))),
    GMAX5 = ifelse(DBH5 >= 9.6 & DBH5 < 12.6, 3,
                   ifelse(DBH5 >= 12.6 & DBH5 <15.6, 2,
                          ifelse(DBH5 >=15.6, 1, 4))),
    GMAX10 = ifelse(DBH10 >= 9.6 & DBH10 < 12.6, 3,
                    ifelse(DBH10 >= 12.6 & DBH10 <15.6, 2,
                           ifelse(DBH10 >=15.6, 1, 4))),
    GMAX17 = ifelse(DBH17 >= 9.6 & DBH17 < 12.6, 3,
                    ifelse(DBH17 >= 12.6 & DBH17 <15.6, 2,
                           ifelse(DBH17 >=15.6, 1, 4))),
    GMAX35 = ifelse(DBH35 >= 9.6 & DBH35 < 12.6, 3,
                    ifelse(DBH35 >= 12.6 & DBH35 <15.6, 2,
                           ifelse(DBH35 >=15.6, 1, 4))),
    GDIFF0 = G0-GMAX0,
    GDIFF5 = G5-GMAX5,
    GDIFF10 = G10-GMAX10,
    GDIFF17 = G17-GMAX17,
    GDIFF35 = G35-GMAX35,
```

```
    GFACT0 = ifelse(GDIFF0 == 0, 1, 0),
    GFACT5 = ifelse(GDIFF5 == 0, 1, 0),
    GFACT10 = ifelse(GDIFF10 == 0, 1, 0),
    GFACT17 = ifelse(GDIFF17 == 0, 1, 0),
    GFACT35 = ifelse(GDIFF35 == 0, 1, 0)
  )

ctr <- ctr%>%
  select(
    Order, Plot, Treatment, ID, Classification, Species.Name,
    Damage, Severity,
    REC0, REC5, REC10, REC17, REC35,
    CC0, CC5, CC10, CC17, CC35,
    PREDBH, DBH0, DBH5, DBH10, DBH17, DBH35,
    VOL0, VOL5, VOL10, VOL17, VOL35,
    G0, G5, G10, G17, G35,
    PRODUCT,
    STUMPAGE0, STUMPAGE5, STUMPAGE10, STUMPAGE17, STUMPAGE35.2,
STUMPAGE35,
    VALUE0, VALUE5, VALUE10, VALUE17, VALUE35.2,VALUE35,
    GMAX0, GMAX5, GMAX10, GMAX17, GMAX35,
    GFACT0, GFACT5, GFACT10, GFACT17, GFACT35,
    MORT0, MORT5, MORT10, MORT17, MORT35,
    STEMS0, STEMS5, STEMS10, STEMS17, STEMS35,
    REMARKS0, REMARKS5, REMARKS10, REMARKS17, REMARKS35)

#write csv
write_csv(ctr, "ctr_full+vol.csv")

# "Gather" Tidy Dataset -----------------------------------------------
------

#Create independent tbl_df for each variable using gather(),
#which takes multiple columns and collapses them into key/value pairs
#for example,
#CC0 CC5 CC10
#   4   4   4
#   3   3 2
#becomes…
#Key        Value
#CC0        4
#CC0        3
#CC5        4
#CC5        3
#CC10   4
#CC10   2

#I also rename each column as the Year of re-measurement, using Year as
the Key

#Crown Class
crown.class <- ctr%>%
  select(1:6,"CC0","CC5","CC10","CC17","CC35") %>%
  rename('1983'=CC0, '1989'=CC5, '1994'=CC10, '2001'=CC17, '2019'=CC35)
%>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Crown.Class")
```

```
#DBH
dbh <- ctr%>%
  select(1:6, "DBH0", "DBH5", "DBH10", "DBH17", "DBH35") %>%
  rename('1983'=DBH0, '1989'=DBH5, '1994'=DBH10, '2001'=DBH17,
'2019'=DBH35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Dbh")%>%
  select(8)
#Recruitment (ingrowth)
ingrowth <- ctr%>%
  select(1:6, "REC0", "REC5", "REC10", "REC17", "REC35") %>%
  rename('1983'=REC0, '1989'=REC5, '1994'=REC10, '2001'=REC17,
'2019'=REC35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Ingrowth")%>%
  select(8)
#DBH from previous measurement
predbh <- ctr %>%
  select(1:6,"PREDBH", "DBH0", "DBH5", "DBH10", "DBH17") %>%
  rename('1983'=PREDBH, '1989'=DBH0, '1994'=DBH5, '2001'=DBH10,
'2019'=DBH17) %>%
  gather('1983','1989','1994','2001', '2019',
         key = "Year", value="Previous.Dbh")%>%
  select(8)
#Crop-tree Grade
grade <- ctr%>%
  select(1:6, "G0", "G5", "G10", "G17", "G35") %>%
  rename('1983'=G0, '1989'=G5, '1994'=G10, '2001'=G17, '2019'=G35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Grade")%>%
  select(8)
#Crop-tree maximum potential grade
gmax <- ctr%>%
  select(1:6, "GMAX0", "GMAX5", "GMAX10", "GMAX17", "GMAX35") %>%
  rename('1983'=GMAX0, '1989'=GMAX5, '1994'=GMAX10, '2001'=GMAX17,
'2019'=GMAX35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Max.Grade")%>%
  select(8)
#Factor of difference betwen actual and potential grade (where 1 = no
difference; maximized grade)
gfact <- ctr%>%
  select(1:6, "GFACT0", "GFACT5", "GFACT10", "GFACT17", "GFACT35") %>%
  rename('1983'=GFACT0, '1989'=GFACT5, '1994'=GFACT10, '2001'=GFACT17,
'2019'=GFACT35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Grade.Factor")%>%
  select(8)
#Product
product <- ctr%>%
  select(1:6, "PRODUCT")%>%
  mutate(
    "1983" = NA,
    "1989" = NA,
    "1994" = NA,
    "2001" = NA
  )%>%
```

```
  rename("2019" = PRODUCT)%>%
  gather( "1983", "1989", "1994", "2001", "2019",
          key = "Year", value = "Product")%>%
  select(8)
#Stumpage+Product
stumpage.product <- ctr%>%
  select(1:6, "STUMPAGE35")%>%
  mutate(
    "1983" = NA,
    "1989" = NA,
    "1994" = NA,
    "2001" = NA
  )%>%
  rename("2019" = STUMPAGE35)%>%
  gather( "1983", "1989", "1994", "2001", "2019",
          key = "Year", value = "Stumpage.Product")%>%
  select(8)
#Stumpage
stumpage <- ctr%>%
  select(1:6, "STUMPAGE0", "STUMPAGE5", "STUMPAGE10", "STUMPAGE17",
"STUMPAGE35.2")%>%
  rename("1983" = STUMPAGE0, "1989" = STUMPAGE5, "1994" = STUMPAGE10,
"2001" = STUMPAGE17, "2019" = STUMPAGE35.2)%>%
  gather( "1983", "1989", "1994", "2001", "2019",
          key = "Year", value = "Stumpage")%>%
  select(8)
#Value+Product
value.product <- ctr%>%
  select(1:6, "VALUE35")%>%
  mutate(
    "1983" = NA,
    "1989" = NA,
    "1994" = NA,
    "2001" = NA
  )%>%
  rename("2019" = VALUE35)%>%
  gather( "1983", "1989", "1994", "2001", "2019",
          key = "Year", value = "Value.Product")%>%
  select(8)
#Value
value <- ctr%>%
  select(1:6, "VALUE0", "VALUE5", "VALUE10", "VALUE17", "VALUE35.2")%>%
  rename("1983" = VALUE0, "1989" = VALUE5, "1994" = VALUE10, "2001" =
VALUE17, "2019" = VALUE35.2)%>%
  gather( "1983", "1989", "1994", "2001", "2019",
          key = "Year", value = "Value")%>%
  select(8)
#Mortality
mortality <- ctr%>%
  select(1:6, "MORT0", "MORT5", "MORT10", "MORT17", "MORT35") %>%
  rename('1983'=MORT0, '1989'=MORT5, '1994'=MORT10, '2001'=MORT17,
'2019'=MORT35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Mortality")%>%
  select(8)
#Number of Stems
stems <- ctr%>%
```

```
  select(1:6, "STEMS0", "STEMS5", "STEMS10", "STEMS17", "STEMS35") %>%
  rename('1983'=STEMS0, '1989'=STEMS5, '1994'=STEMS10, '2001'=STEMS17,
'2019'=STEMS35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Stems")%>%
  select(8)
#Remarks
remarks <- ctr%>%
  select(1:6, "REMARKS0", "REMARKS5", "REMARKS10", "REMARKS17",
"REMARKS35") %>%
  rename('1983'=REMARKS0, '1989'=REMARKS5, '1994'=REMARKS10,
'2001'=REMARKS17, '2019'=REMARKS35) %>%
  gather('1983','1989','1994','2001','2019',
         key = "Year", value="Remarks")%>%
  select(8)
#Butt-log Volume
volume <- ctr%>%
  select(1:6, "VOL0", "VOL5", "VOL10", "VOL17", "VOL35")%>%
  rename("1983" = VOL0, "1989" = VOL5, "1994" = VOL10, "2001" = VOL17,
"2019" = VOL35)%>%
  gather("1983", "1989", "1994", "2001", "2019",
         key = "Year", value = "Volume")%>%
  select(8)

#Combine independent datasets into one “tidy” dataset using cbind()
ctr.tidy<-
cbind(crown.class,predbh,ingrowth,dbh,volume,grade,gmax,gfact,product,s
tumpage,stumpage.product,value,value.product,stems,mortality,remarks)

# Export Tidy CSV -----------------------------------------------------
---------

#Write .csv
write_csv(ctr.tidy, "ctr_tidy.csv")



# Create Plot-Level Variables/Summaries for Statistic Analyses ####

# Crop-trees ####

#pai dbh
pai.dbh <- ctr %>%
  filter(Classification == "crop-tree" & !is.na(DBH35))%>%
  mutate(
    "0to5" = (DBH5-DBH0)/5,
    "5to10" = (DBH10-DBH5)/5,
    "10to17" = (DBH17-DBH10)/7,
    "17to35" = (DBH35-DBH17)/18
  )%>%
  select(
    Plot, Treatment,
    "0to5","5to10","10to17","17to35"
  )%>%
  pivot_longer(
    c(3:6), names_to = "Period", values_to = "PAI.dbh"
  )%>%
```

```
  group_by(
    Plot,
    Treatment,
    Period
  )%>%
  summarize(
    PAI.dbh=mean(PAI.dbh)
  )%>%
  ungroup()

#avg dbh
avg.dbh <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(DBH35))%>%
  group_by(
    Plot, Treatment
  )%>%
  summarize(
    "1983" = mean(DBH0, na.rm=T),
    "1989" = mean(DBH5, na.rm=T),
    "1993" = mean(DBH10, na.rm=T),
    "2001" = mean(DBH17, na.rm=T),
    "2019" = mean(DBH35, na.rm=T)
  )%>%
  pivot_longer(
    c(3:7), names_to = "Year", values_to = "dbh"
  )

#MaxPG
maxpg <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(G35))%>%
  select(
    Plot, Treatment, ID,
    GFACT0, GFACT5, GFACT10, GFACT17, GFACT35
  )%>%
  rename(
    "1983" = GFACT0,
    "1989" = GFACT5,
    "1993" = GFACT10,
    "2001" = GFACT17,
    "2019" = GFACT35
  )%>%
  pivot_longer(
    c(4:8), names_to = "Year", values_to = "Potential.Grade"
  )%>%
  group_by(Plot,
           Treatment,
           Year)%>%
  summarize(
    Success = length(Potential.Grade[which(Potential.Grade==1)]),
    Failure = length(Potential.Grade[which(Potential.Grade==0)])
  )

#Per-crop-tree value and volume in 2019
ct.value <- ctr %>%
  filter(Classification == "crop-tree" & !is.na(G35))%>%
  group_by(Plot)%>%
  top_n(10, VALUE35)%>%
```

```
  group_by(Plot, Treatment)%>%
  summarize(
    volume = mean(VOL35, na.rm=T), #butt-log
    value = mean(VALUE35, na.rm=T) #butt-log
  )

treat.ct.value <- ct.value%>%
  group_by(Treatment)%>%
  summarize(
    Mean.Value = mean(value),
    SE.Value = stderr(value)
  )

# Stand-level ####

#Value per acre (NPV)

# Calculate value of non-crop-trees

value<-ctr%>%
  filter(Classification != "crop-tree" & Classification != "removed" &
DBH35 >= 9.6 & !is.na(DBH35) & Species.Name != "eastern_hemlock")%>%
  mutate(
    Species.Group =
      ifelse(Species.Name == "basswood"
             | Species.Name == "black_walnut"
             | Species.Name == "blackgum"
             | Species.Name == "butternut"
             | Species.Name == "white_ash",
             "Other",
             ifelse(Species.Name == "yellow-poplar"
                    | Species.Name == "cucumbertree",
                    "Magnolia",
                    ifelse(Species.Name == "white_oak",
                           "White_Oak",
                           ifelse(Species.Name == "black_oak"
                                  | Species.Name == "northern_red_oak"
                                  | Species.Name == "scarlet_oak",
                                  "Red_Oak",
                                  ifelse(Species.Name ==
"chestnut_oak",
                                         "Chestnut_Oak",
                                         ifelse(Species.Name ==
"red_maple",
                                                "Red_Maple",
                                                ifelse(Species.Name ==
"American_beech",
                                                       "Beech",

ifelse(Species.Name == "mockernut_hickory"
                                                              |
Species.Name == "pignut_hickory"
                                                              |
Species.Name == "shagbark_hickory",

"Hickory", NA)))))))), #create species groups
    Diameter.Class = ifelse(DBH35 >=9.6 & DBH35 < 12.6, 3,
```

```
                            ifelse(DBH35 >= 12.6 & DBH35 < 15.6, 2,
                                   ifelse(DBH35 >= 15.6, 1, NA)))
#create diameter classes
  )%>%
  group_by(
    Plot,
    Treatment,
    Diameter.Class,
    Species.Group
  )%>%
  summarize(
    TPA = tpa(DBH35, 2, na.rm=T), #calculate number of trees per acre
in each category
    Value.Per.Tree = mean(VALUE35, na.rm=T), #calculate value subsample
tree represents
    Value.Per.Acre = TPA*Value.Per.Tree #calculate value per acre for
species group and diameter class
    )%>%
  group_by(
    Plot,
    Treatment
  )%>%
  summarize(
    value.noncroptrees = sum(Value.Per.Acre) #sum values to find total
value per acre of non-crop-trees
  )

#Calculate crop-tree value per acre

value.croptrees <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(VALUE35))%>%
  group_by(Plot, Treatment)%>%
  summarize(
    value.croptrees = sum(VALUE35*2)
  )

#Calculate removed trees value per acre

value.pertree <- ctr%>% #calculate average stumpage price per tree in
each diameter class by plot
  filter(Classification == "non-crop-tree" | Classification ==
"ingrowth")%>%
  mutate(Diameter.Class = ifelse(DBH35 >=9.6 & DBH35 < 12.6, 3,
                                 ifelse(DBH35 >= 12.6 & DBH35 < 15.6,
2,
                                        ifelse(DBH35 >= 15.6, 1, NA)))
  )%>%
  group_by(Plot, Treatment, Diameter.Class)%>%
  summarize(
    TPA = tpa(VALUE35, 1, na.rm=T),
    Stumpage = sum(STUMPAGE35, na.rm=T),
    Pertree.Stumpage = Stumpage/TPA
  )%>%
  filter(!is.na(Diameter.Class) & Treatment != "Control")%>%
  select(
    Plot, Treatment, Diameter.Class, Pertree.Stumpage
  )
```

```
value.removed <- ctr%>% #multiply average stumpage price by per acre
butt-log volume to find value (2019 terms) of removed trees in 1983
  filter(DBH0 >= 9.6 & Classification == "removed")%>%
  mutate(Diameter.Class = ifelse(DBH0 >=9.6 & DBH0 < 12.6, 3,
                              ifelse(DBH0 >= 12.6 & DBH0 < 15.6, 2,
                                     ifelse(DBH0 >= 15.6, 1, NA)))
  )%>%
  group_by(Plot, Treatment, Diameter.Class)%>%
  summarize(
    Volume = sum(VOL0, na.rm=T)*2
  )%>%
  left_join(value.pertree)%>%
  mutate(
    value.removed = (Volume*Pertree.Stumpage)/1000
  )%>%
  group_by(Plot,Treatment)%>%
  summarize(
    value.removed = sum(value.removed)
  )


#Add crop-tree and removed value to calculate net present value (NPV)

value <- value%>%
  left_join(value.croptrees)%>%
  left_join(value.removed)

value$value.removed[which(is.na(value$value.removed))] <- 0 #set
removed value to 0 for control

value$NPV <-
value$value.noncroptrees+value$value.croptrees+value$value.removed
#calculate NPV by adding all three value variables

treat.npv <- value%>%
  group_by(Treatment)%>%
  summarize(
    Mean.NPV = mean(NPV),
    SE.NPV = stderr(NPV)
  )

#Basal area per acre & percent stocking

standlevel <- ctr.tidy%>%
  filter(Classification != "removed")%>%
  group_by(Plot, Treatment, Year)%>%
  summarize(
    TPA = tpa(Dbh, 2, na.rm=T),
    BA = ba(Dbh, 2), #per acre in square feet
    Percent.Stocking = percent.stocking(2, Dbh)
  )

percent.stocking.stand <- standlevel %>%
  group_by(Treatment, Year)%>%
  summarize(
```

```
    mean.PS = mean(Percent.Stocking),
    SE.PS = stderr(Percent.Stocking)
  )

treat.percent.stocking <- ctr.tidy%>%
  filter(Classification != "removed")%>%
  group_by(Plot,Treatment,Year)%>%
  summarize(
    TPA = tpa(Dbh, 2, na.rm=T),
    BA = ba(Dbh, 2), #per acre in square feet
    Percent.Stocking = percent.stocking(2, Dbh)
  )%>%
  group_by(Treatment)%>%
  summarize(
    Mean.Percent.Stocking = mean(Percent.Stocking),
    SE.Percent.Stocking = stderr(Percent.Stocking)
  )

year.percent.stocking <- ctr.tidy%>%
  filter(Classification != "removed")%>%
  group_by(Plot,Treatment,Year)%>%
  summarize(
    TPA = tpa(Dbh, 2, na.rm=T),
    BA = ba(Dbh, 2), #per acre in square feet
    Percent.Stocking = percent.stocking(2, Dbh)
  )%>%
  group_by(Year)%>%
  summarize(
    Mean.Percent.Stocking = mean(Percent.Stocking),
    SE.Percent.Stocking = stderr(Percent.Stocking)
  )

#Ingrowth

ingrowth <- ctr%>%
  filter(Classification == "ingrowth")%>%
  mutate(
    Species = ifelse(
      Species.Name == "scarlet_oak"
      | Species.Name == "northern_red_oak"
      | Species.Name == "black_oak"
      | Species.Name == "chestnut_oak",
      "red_oak",
      ifelse(
        Species.Name == "white_oak",
        "white_oak",
        ifelse(
          Species.Name == "shagbark_hickory"
          | Species.Name == "hickory_spp"
          | Species.Name == "mockernut_hickory"
          | Species.Name == "pignut_hickory",
          "hickory",
          ifelse(
            Species.Name == "bigleaf_magnolia"
            | Species.Name == "cucumbertree"
            | Species.Name == "mountain_magnolia"
            | Species.Name == "yellow-poplar",
```

```
            "magnolia",
            ifelse(Species.Name == "red_maple"
                   |Species.Name == "sugar_maple",
                   "maple",
                   ifelse(Species.Name == "American_beech",
                          "beech",
                          ifelse(Species.Name == "blackgum",
                                 "blackgum",
                                 ifelse(Species.Name ==
"eastern_hemlock",
                                        "eastern_hemlock",
                                        ifelse(Species.Name ==
"eastern_redbud"
                                               |Species.Name ==
"flowering_dogwood"
                                               |Species.Name ==
"serviceberry"
                                               |Species.Name ==
"rhododendron",

"flowering_shrubs","other")))))))))
  )%>%
  group_by(Plot,Treatment,Species)%>%
  summarize(
    Ingrowth = tpa(DBH35, 2, na.rm = T)
  )

total.ingrowth <- ingrowth%>%
  group_by(Plot, Treatment)%>%
  summarize(
    Total.Ingrowth = sum(Ingrowth)
  )

ingrowth <- ingrowth%>%
  left_join(total.ingrowth)%>%
  mutate(
    percent.ingrowth = (Ingrowth/Total.Ingrowth)*100
  )

treat.ingrowth.species <- ingrowth%>%
  group_by(Treatment, Species)%>%
  summarize(
    Percent.Ingrowth = mean(percent.ingrowth)
  )

write_csv(treat.ingrowth.species, "ingrowth.csv")

# Statistical Analyses ####

# Crop-trees ANOVAs ####

#avg.dbh
avg.dbh.lm <- lm(dbh~Treatment*Year,
                 contrasts=list(Treatment=contr.sum,
                                Year=contr.sum),
                 data=avg.dbh)
Anova(avg.dbh.lm, type=3) #main effects significant
```

```
#post-hoc tests avg.dbh
treatmeans.avg.dbh <- emmeans(avg.dbh.lm, "Treatment")
contrast(treatmeans.avg.dbh, "pairwise")

yearmeans.avg.dbh <- emmeans(avg.dbh.lm, "Year")
contrast(yearmeans.avg.dbh, "pairwise")

#pai.dbh
pai.dbh.lm <- lm(PAI.dbh~Treatment*Period,
                 contrasts=list(Treatment=contr.sum,
                                Period=contr.sum),
                 data=pai.dbh)
Anova(pai.dbh.lm, type=3)

#post-hoc tests pai.dbh
treatmeans.pai.dbh <- emmeans(pai.dbh.lm, "Treatment")
contrast(treatmeans.pai.dbh, "pairwise")

periodmeans.pai.dbh <- emmeans(pai.dbh.lm, "Period")
contrast(periodmeans.pai.dbh, "pairwise")

#binomial test MaxPG
maxpg.glm <- glm(cbind(Success, Failure)~Treatment*Year,
                     family = "binomial",
                     contrasts = list(Treatment=contr.sum,
                                      Year=contr.sum),
                     data=maxpg)
summary(maxpg.glm)
Anova(maxpg.glm, type=3)

#post-hoc tests MaxPG
treatmeans.maxpg.glm <- emmeans(maxpg.glm, "Treatment")
contrast(treatmeans.maxpg.glm, "pairwise")

yearmeans.maxpg.glm <- emmeans(maxpg.glm, "Year")
contrast(yearmeans.maxpg.glm, "pairwise")

#per-crop-tree value in 2019
ct.value.lm <- lm(value~Treatment,
                  contrasts=list(Treatment=contr.sum),
                  data=ct.value)
Anova(ct.value.lm, type=3) #no significance

# Stand-level ANOVAs ####

#NPV (2019)
npv.lm <- lm(NPV~Treatment,
             contrasts=list(Treatment=contr.sum),
             data=value)
Anova(npv.lm, type=3) #no significance

#BA per acre
ba.lm <- lm(BA~Treatment*Year,
            contrasts=list(Treatment=contr.sum,
                           Year=contr.sum),
            data=standlevel)
```

```
Anova(ba.lm, type=3) #interaction effect significant

#post-hoc tests BA per acre
treatmeans.ba.lm <- emmeans(ba.lm, "Treatment", by="Year")
contrast(treatmeans.ba.lm, "pairwise")

yearmeans.ba.lm <- emmeans(ba.lm, "Year", by="Treatment")
contrast(yearmeans.ba.lm, "pairwise")

#Percent stocking
ps.lm <- lm(Percent.Stocking~Treatment*Year,
            contrasts=list(Treatment=contr.sum,
                           Year=contr.sum),
            data=standlevel)
Anova(ps.lm, type=3)

#post-hoc tests percent stocking
treatmeans.ps.lm <- emmeans(ps.lm, "Treatment")
contrast(treatmeans.ps.lm, "pairwise")

yearmeans.ps.lm <- emmeans(ps.lm, "Year")
contrast(yearmeans.ps.lm, "pairwise")

#Ingrowth
total.ingrowth <- ctr%>%
  filter(Classification == "ingrowth")%>%
  group_by(Plot, Treatment)%>%
  summarize(
    Total.Ingrowth = tpa(DBH35, 2, na.rm=T)
  )

treat.ingrowth <- total.ingrowth%>%
  group_by(Treatment)%>%
  summarize(
    Mean.Ingrowth = mean(Total.Ingrowth),
    SE.Ingrowth = stderr(Total.Ingrowth)
  )

ingrowth.lm <- lm(Total.Ingrowth~Treatment,
                  contrasts=list(Treatment=contr.sum),
                  data=total.ingrowth)
Anova(ingrowth.lm, type=3) #no significance

# Extras ####

# Stocking by tree "category" and crown class####

#Categories: crop-tree, non-crop-tree, ingrowth
ps.categories <- ctr.tidy%>%
  filter(Classification != "removed")%>%
  group_by(Plot, Treatment, Year, Classification)%>%
  summarize(
    Percent.Stocking = percent.stocking(2, Dbh)
  )%>%
  group_by(Treatment, Year, Classification)%>%
  summarize(
    Percent.Stocking = mean(Percent.Stocking)
```

```
  )

write_csv(ps.categories, "stocking_by_cat.csv")

#Crown classes
ps.crownclass <- ctr.tidy%>%
  filter(Classification != "removed")%>%
  mutate(
    Canopy.Position = ifelse(Crown.Class == 1 | Crown.Class == 2,
"Upper",
                             ifelse(Crown.Class == 3, "Intermediate",
"Understory"))
  )%>%
  filter(!is.na(Canopy.Position))%>%
  group_by(Plot, Treatment, Year, Canopy.Position)%>%
  summarize(
    Percent.Stocking = percent.stocking(2, Dbh)
  )%>%
  group_by(Treatment, Year, Canopy.Position)%>%
  summarize(
    Percent.Stocking = mean(Percent.Stocking)
  )

write_csv(ps.crownclass, "stocking_by_crown.csv")

# % of Value Represented by Crop-trees ####

top6.ct <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(DBH35))%>%
  group_by(Plot, Treatment)%>%
  top_n(.,3,VALUE35)%>%
  summarize(
    Top6 = sum(VALUE35*2)
  )

top12.ct <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(DBH35))%>%
  group_by(Plot, Treatment)%>%
  top_n(.,6,VALUE35)%>%
  summarize(
    Top12 = sum(VALUE35*2)
  )

top20.ct <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(DBH35))%>%
  group_by(Plot, Treatment)%>%
  top_n(.,10,VALUE35)%>%
  summarize(
    Top20 = sum(VALUE35*2, na.rm=T)
  )

all.ct <- ctr%>%
  filter(Classification == "crop-tree" & !is.na(DBH35))%>%
  group_by(Plot, Treatment)%>%
  summarize(
    All = sum(VALUE35*2, na.rm=T)
  )
```

```
percent.value.ct <- value%>%
  select(Plot, Treatment, Noncroptrees = value.noncroptrees, Removed =
value.removed, NPV)%>%
  left_join(top6.ct)%>%
  left_join(top12.ct)%>%
  left_join(top20.ct)%>%
  left_join(all.ct)%>%
  mutate(
    percent.top6 = (Top6/NPV)*100,
    percent.top12 = (Top12/NPV)*100,
    percent.top20 = (Top20/NPV)*100,
    percent.all = (All/NPV)*100
  )%>%
  group_by(Treatment)%>%
  summarize(
    Top6 = mean(percent.top6),
    Top12 = mean(percent.top12),
    Top20 = mean(percent.top20),
    All = mean(percent.all)
  )

write_csv(percent.value.ct, "percent_value.csv")

# Appendix A: Stand Summary Tables ####
# Pre-treatment and removed trees summaries ####

# Pre-treatment####

#Pre-treatment stand-level
pretreat.plots <- ctr.tidy%>%
  filter(Year==1983)%>%
  group_by(Plot,
           Treatment)%>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Stocking" = percent.stocking(2, Dbh),
            "Vol.acre" = sum(Volume*2, na.rm=T),
            "avgDBH" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "QMD" = qmd(BA, TPA),
    "SI" = case_when(
      Plot=="1" ~ 75,
      Plot=="2" ~ 76,
      Plot=="3" ~ 65,
      Plot=="4" ~ 83,
      Plot=="5" ~ 74,
      Plot=="6" ~ 69,
      Plot=="7" ~ 68,
      Plot=="8" ~ 69,
      Plot=="9" ~ 69,
      Plot=="10" ~ 77,
      Plot=="11" ~ 75,
      Plot=="12" ~ 77
    ),
    "Age" = case_when(
```

```
      Plot=="1" ~ 81,
      Plot=="2" ~ 72,
      Plot=="3" ~ 62,
      Plot=="4" ~ 67,
      Plot=="5" ~ 52,
      Plot=="6" ~ 70,
      Plot=="7" ~ 70,
      Plot=="8" ~ 65,
      Plot=="9" ~ 80,
      Plot=="10" ~ 82,
      Plot=="11" ~ 99,
      Plot=="12" ~ 82
    )
  )%>%
  select(Plot,
         Treatment,
         avgDBH,
         QMD,
         TPA,
         BA,
         Stocking,
         Vol.acre)

pretreat.treat <- ctr.tidy%>%
  filter(Year==1983)%>%
  group_by(Plot,
           Treatment)%>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Stocking" = percent.stocking(2, Dbh),
            "Vol.acre" = sum(Volume*2, na.rm=T),
            "avgDBH" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "QMD" = qmd(BA, TPA),
    "SI" = case_when(
      Plot=="1" ~ 75,
      Plot=="2" ~ 76,
      Plot=="3" ~ 65,
      Plot=="4" ~ 83,
      Plot=="5" ~ 74,
      Plot=="6" ~ 69,
      Plot=="7" ~ 68,
      Plot=="8" ~ 69,
      Plot=="9" ~ 69,
      Plot=="10" ~ 77,
      Plot=="11" ~ 75,
      Plot=="12" ~ 77
    ),
    "Age" = case_when(
      Plot=="1" ~ 81,
      Plot=="2" ~ 72,
      Plot=="3" ~ 62,
      Plot=="4" ~ 67,
      Plot=="5" ~ 52,
      Plot=="6" ~ 70,
      Plot=="7" ~ 70,
```

```
      Plot=="8" ~ 65,
      Plot=="9" ~ 80,
      Plot=="10" ~ 82,
      Plot=="11" ~ 99,
      Plot=="12" ~ 82
    )
  )%>%
  ungroup()%>%
  select(-Plot)%>%
  group_by(Treatment)%>%
  summarize_all(c("mean","stderr"))

#Pre-treatment crop-tree summaries
croptrees.pretreatment <- ctr.tidy%>%
  filter(Year==1983 & Classification=="crop-tree")%>%
  group_by(Plot,
           Treatment)%>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Stocking" = percent.stocking(2, Dbh),
            "Vol.tree" = (sum(Volume*2, na.rm=T))/(tpa(which(Dbh>=9.6),
2, na.rm=T)),
            "Vol.acre" = sum(Volume*2, na.rm=T),
            "avgDBH" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "QMD" = qmd(BA, TPA)
  )%>%
  select(Plot,
         Treatment,
         avgDBH,
         QMD,
         TPA,
         BA,
         Stocking,
         Vol.tree,
         Vol.acre)


# Removed trees####
#Removed trees 1983
removed.plots <- ctr.tidy%>% #by plot
  filter(Year==1983 & Classification=="removed")%>%
  group_by(Plot,
           Treatment)%>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Vol.acre" = sum(Volume*2, na.rm=T),
            "avgDBH" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "QMD" = qmd(BA, TPA)
  )%>%
  select(Plot,
         Treatment,
         avgDBH,
         QMD,
```

```
         TPA,
         BA,
         Vol.acre)

removed.treat <- ctr.tidy%>% #by treatment
  filter(Year==1983 & Classification=="removed")%>%
  group_by(Plot,
           Treatment)%>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Vol.acre" = sum(Volume*2, na.rm=T),
            "avgDBH" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "QMD" = qmd(BA, TPA)
  )%>%
  ungroup()%>%
  select(-Plot)%>%
  group_by(Treatment)%>%
  summarize_all(c("mean", "stderr"))


# Post-treatment ####

posttreat.plots <- ctr.tidy%>% #by plot
  filter(Year==1983 & Classification != "removed")%>%
  group_by(Plot,
           Treatment)%>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Stocking" = percent.stocking(2, Dbh),
            "Vol.acre" = sum(Volume*2, na.rm=T),
            "avgDBH" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "QMD" = qmd(BA,TPA),
    "SI" = case_when(
      Plot=="1" ~ 75,
      Plot=="2" ~ 76,
      Plot=="3" ~ 65,
      Plot=="4" ~ 83,
      Plot=="5" ~ 74,
      Plot=="6" ~ 69,
      Plot=="7" ~ 68,
      Plot=="8" ~ 69,
      Plot=="9" ~ 69,
      Plot=="10" ~ 77,
      Plot=="11" ~ 75,
      Plot=="12" ~ 77
    ),
    "Age" = case_when(
      Plot=="1" ~ 81,
      Plot=="2" ~ 72,
      Plot=="3" ~ 62,
      Plot=="4" ~ 67,
      Plot=="5" ~ 52,
      Plot=="6" ~ 70,
```

```
        Plot=="7" ~ 70,
        Plot=="8" ~ 65,
        Plot=="9" ~ 80,
        Plot=="10" ~ 82,
        Plot=="11" ~ 99,
        Plot=="12" ~ 82
      )
    )%>%
    select(Plot,
           Treatment,
           avgDBH,
           QMD,
           TPA,
           BA,
           Stocking,
           Vol.acre)

  posttreat.treat <- ctr.tidy%>%
    filter(Year==1983 & Classification != "removed")%>%
    group_by(Plot,
             Treatment)%>%
    summarize("TPA" = tpa(Dbh, 2, na.rm=T),
              "BA" = ba(Dbh, 2),
              "Stocking" = percent.stocking(2, Dbh),
              "Vol.acre" = sum(Volume*2, na.rm=T),
              "avgDBH" = mean(Dbh, na.rm=T)
    )%>%
    mutate(
      "QMD" = qmd(BA, TPA),
      "SI" = case_when(
        Plot=="1" ~ 75,
        Plot=="2" ~ 76,
        Plot=="3" ~ 65,
        Plot=="4" ~ 83,
        Plot=="5" ~ 74,
        Plot=="6" ~ 69,
        Plot=="7" ~ 68,
        Plot=="8" ~ 69,
        Plot=="9" ~ 69,
        Plot=="10" ~ 77,
        Plot=="11" ~ 75,
        Plot=="12" ~ 77
      ),
      "Age" = case_when(
        Plot=="1" ~ 81,
        Plot=="2" ~ 72,
        Plot=="3" ~ 62,
        Plot=="4" ~ 67,
        Plot=="5" ~ 52,
        Plot=="6" ~ 70,
        Plot=="7" ~ 70,
        Plot=="8" ~ 65,
        Plot=="9" ~ 80,
        Plot=="10" ~ 82,
        Plot=="11" ~ 99,
        Plot=="12" ~ 82
      )
```

```
  )%>%
  ungroup()%>%
  select(-Plot)%>%
  group_by(Treatment)%>%
  summarize_all(c("mean","stderr"))

# Appendix B: Plots ####

# Plot summaries ####
plotsums <- ctr.tidy %>%
  mutate(Year = as.numeric(Year))%>%
  filter(Classification != "removed" | Year != 1983) %>%
  group_by(Plot,
           Treatment,
           Year) %>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Stocking" = percent.stocking(2, Dbh),
            "Volume.tree" = (sum(Volume*2,
na.rm=T))/(tpa(which(Dbh>=9.6), 2, na.rm=T)),
            "Volume.acre" = sum(Volume*2, na.rm=T),
            "dbh" = mean(Dbh, na.rm=T),
            "Ingrowth" = (2*length(which(Ingrowth==1))), #per acre
            "Mortality" = (2*length(which(Mortality==T))) #per acre
  )%>%
  mutate(
    "qmd" = qmd(BA, TPA),
    "Ingrowth" = cumsum(Ingrowth),
    "Total_Mortality" = cumsum(Mortality)
  )%>%
  left_join(SI.AGE)%>%
  select("Plot",
         "Treatment",
         "Year",
         "Age",
         "SI",
         "Ingrowth",
         "TPA",
         "Mortality",
         "Total_Mortality",
         "qmd",
         "dbh",
         "BA",
         "Stocking",
         "Volume.tree",
         "Volume.acre")

#Take the mean and standard error of plot summaries
treatsums <- plotsums%>%
  ungroup()%>%
  select(-Plot)%>%
  group_by(Treatment,
           Year) %>%
  summarize_all(
    list(Mean = mean, SE = stderr)
  )
```

```
#Summary statistics

#use pivot_longer to create a table with each Variable in one column
#and the corresponding value in another column ("x")
#then group_by treatment, year, and variable
#and summarize using typical summary stats
summarystats <- plotsums %>%
  pivot_longer(c(4:15), names_to = "Variable", values_to = "x")  %>%
  group_by(
    Treatment, Year, Variable
  ) %>%
  summarize(
    Number = length(x),
    Min = min(x),
    First_Quartile = quantile(x, 0.25),
    Median = median(x),
    Third_Quartile = quantile(x, 0.75),
    Max = max(x),
    Mean = mean(x),
    St.Dev = sd(x)
  )

#write summary stats as a .csv file
write_csv(summarystats, "summary_stats.csv")

#Create plots over time for all trees

#remove standard error in order to iterate over dataset
treatmeans <- treatsums%>%
  select(Treatment,
         Year,
         ends_with("Mean"))%>%
  ungroup()%>%
  select(
    "Treatment",
    "Year",
    "Ingrowth" = "Ingrowth_Mean",
    "TPA" = "TPA_Mean",
    "Mortality" = "Mortality_Mean",
    "Total_Mortality" = "Total_Mortality_Mean",
    "qmd" = "qmd_Mean",
    "dbh" = "dbh_Mean",
    "BA" = "BA_Mean",
    "Percent_Stocking" = "Stocking_Mean",
    "Volume_per_tree" = "Volume.tree_Mean",
    "Volume_per_acre" = "Volume.acre_Mean"
  )%>%
  mutate(
    Treatment = as.factor(Treatment)
  )


#write chart function
ctrcharts = function(x,y) {
  ggplot(treatmeans, aes_string(x=x, y = y,
color=treatmeans$Treatment)) +
```

```
    scale_color_manual(values=c("Control"="black", "20_CTR"="blue",
"34_CTR"="red")) +
    geom_point() +
    geom_line() +
    labs(x=x,
         y=y
    ) +
    theme_classic()
}

#set names of response variables
response = names(treatmeans)
response = set_names(response)

#use map function to iterate over each variable in "treatmeans"
ctr_charts <-
  map(response,
      ~map("Year", ctrcharts, y = .x))

#set names for charts
chartnames <- imap(ctr_charts, ~paste0(.y, "", names(.x), ".png")) %>%
  flatten()

#save files
walk2(chartnames, flatten(ctr_charts), ~ggsave(filename = .x, plot =
.y,
                                                height = 7, width = 7))

# Crop-tree summaries ####
croptrees.tidy <- ctr.tidy%>%
  filter(Classification == "crop-tree")%>%
  filter(Plot != 1 | ID != 154,
         Plot != 1 | ID != 40,
         Plot != 3 | ID != 145,
         Plot != 4 | ID != 15,
         Plot != 5 | ID != 177,
         Plot != 6 | ID != 304,
         Plot != 6 | ID != 39,
         Plot != 6 | ID != 199,
         Plot != 7 | ID != 227,
         Plot != 7 | ID != 117,
         Plot != 8 | ID != 112,
         Plot != 9 | ID != 29,
         Plot != 9 | ID != 89,
         Plot != 10 | ID != 256,
         Plot != 11 | ID != 240,
         Plot != 11 | ID != 111,
         Plot != 11 | ID != 146,
         Plot != 12 | ID != 86,
         Plot != 12 | ID != 147,
         Plot != 12 | ID != 136,
         Plot != 12 | ID != 47,
         Plot != 12 | ID != 38
  ) # filter out crop-trees that died

plotsums.ct <- croptrees.tidy %>%
  group_by(Plot,
```

```
           Treatment,
           Year) %>%
  summarize("TPA" = tpa(Dbh, 2, na.rm=T),
            "BA" = ba(Dbh, 2),
            "Stocking" = percent.stocking(2, Dbh),
            "Volume.tree" = (sum(Volume*2,
na.rm=T))/(tpa(which(Dbh>=9.6), 2, na.rm=T)),
            "Volume.acre" = sum(Volume*2, na.rm=T),
            "dbh" = mean(Dbh, na.rm=T)
  )%>%
  mutate(
    "qmd" = qmd(BA,TPA))%>%
  select("Plot",
         "Treatment",
         "Year",
         "qmd",
         "dbh",
         "BA",
         "Stocking",
         "Volume.tree",
         "Volume.acre")


#Take the mean and standard error of plot summaries
treatsums.ct <- plotsums.ct%>%
  ungroup()%>%
  select(-Plot)%>%
  group_by(Treatment,
           Year) %>%
  summarize_all(
    list(Mean = mean, SE = stderr)
  )


summarystats.ct<-plotsums.ct %>%
  pivot_longer(c(4:9), names_to = "Variable", values_to = "x")%>%
  group_by(
    Treatment, Year, Variable
  ) %>%
  summarize(
    Number = length(x),
    Min = min(x),
    First_Quartile = quantile(x, 0.25),
    Median = median(x),
    Third_Quartile = quantile(x, 0.75),
    Max = max(x),
    Mean = mean(x),
    St.Dev = sd(x)
  )

#write .csv

write_csv(summarystats.ct, "croptrees_summarystats.csv")

#Line Charts

treatmeans.ct <- treatsums.ct%>%
```

```
  select(Treatment,
         Year,
         ends_with("Mean"))%>%
  ungroup()%>%
  select(
    "Treatment",
    "Year",
    "qmd" = "qmd_Mean",
    "dbh" = "dbh_Mean",
    "BA" = "BA_Mean",
    "Percent_Stocking" = "Stocking_Mean",
    "Volume_per_tree" = "Volume.tree_Mean",
    "Volume_per_acre" = "Volume.acre_Mean"
  )%>%
  mutate(
    Treatment = as.factor(Treatment),
    Year = as.numeric(Year)
  )

#write chart function
linecharts = function(x,y) {
  ggplot(treatmeans.ct, aes_string(x=x, y = y,
color=treatmeans.ct$Treatment)) +
    scale_color_manual(values=c("Control"="black", "20_CTR"="blue",
"34_CTR"="red")) +
    geom_point() +
    geom_line() +
    labs(x=x,
         y=y) +
    theme_classic()
}

#set names of response variables
response = names(treatmeans.ct)
response = set_names(response)

line_charts <-
  map(response,
      ~map("Year", linecharts, y = .x))

#set names for charts
chartnames <- imap(line_charts, ~paste0(.y, "", names(.x),
"_croptree.png")) %>%
  flatten()

#save files
walk2(chartnames, flatten(line_charts), ~ggsave(filename = .x, plot =
.y,
                                                height = 7, width = 7))
```

REFERENCES

Abrams, M.D. 1990. Adaptations and responses to drought in *Quercus* species of North America. Tree Physiology 7:227-238.

Abrams, M.D. 2003. Where has all the white oak gone? BioScience 53(10):927-939.

Abrams, M.D., and G.J. Nowacki. 1992. Historical variation in fire, oak recruitment, and post-logging accelerated succession in central Pennsylvania. Bulletin of the Torrey Botanical Club 119(1):19-28.

Beck, D.E. 1987. Management options for southern Appalachian hardwoods: the two-aged stand. P. 451-454 *in* Proceedings of the Fourth biennial southern silvicultural research conference. 1996 November 4-6; Atlanta, GA. General Technical Report SE-42. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Brooke, J.M, P.S. Basinger, J.L. Birckhead, M.A. Lashley, J.M. McCord, J.S. Nanney, and C.A. Harper. 2019. Effects of fertilization and crown release on white oak (*Quercus alba*) masting and acorn quality. Forest Ecology and Management 433:305-312.

Brzostek, E.R., D. Dragoni, H.P. Schmid, A.F. Rahman, D. Sims, C.A. Wayson, D.J. Johnson, and R.P. Phillips. 2014. Chronic water stress reduces tree growth and the carbon sink of deciduous hardwood forests. Global change biology 20(8):2531-2539.

Butler, B.J. 2008. Family forest owners of the United States, 2006.

Cho D.S., and R.E.J. Boerner. 1991. Canopy disturbance patterns and regeneration of *Quercus* species in two Ohio old-growth forests. Vegetatio 93:9-18.

Cleland, D.T., J.A. Freeouf, J.E. Keys, G.J. Nowacki, C.A. Carpenter, and W.H. McNab. 2007. Ecological Subregions: Sections and Subsections for the conterminous United States.

Clotfelter, E.D., A.B. Pedersen, J.A. Cranford, N. Ram, E.A. Snajdr, V. Nolan, and E.D. Ketterson. 2007. Acorn mast drives long-term dynamics of rodent and songbird populations. Oecologia 154(3):493-503.

Dai, A. 2019. The Climate Data Guide: Palmer Drought Severity Index (PDSI). National Center For Atmospheric Research Staff (ed.), https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi.

Dale, M.E. 1968. Growth response from thinning young even-aged white oak stands. P. 19. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Upper Darby, PA.

Demchik, M.C., J.L. Conrad IV, M.M. Vokoun, B. Backes, I. Schellhaass, and B.M. Demchik. 2018. Crop tree release guidelines for 71-to 94-year-old oak stands based on height and financial maturity. Journal of Forestry 116(3):217-221.

Dey, D.C. 2014. Sustaining oak forests in eastern North America: regeneration and recruitment, the pillars of sustainability. Forest Science 60(5):926-942.

Dey, D.C., and R.P. Guyette. 2000. Sustaining Oak Ecosystems in the Central Hardwood Region: Lessons from the Past--Continuing the History of Disturbance. *in* Trans. 65th No. Amer. Wildl. and Natur. Resour. Conf. p. 170-183.

Dey, D.C., A.A. Royo, P.H. Brose, T.F. Hutchinson, M.A. Spetich, and S.H. Stoleson. 2010. An ecologically based approach to oak silviculture: a synthesis of 50 years of oak ecosystem research in North America. Colombia Forestal 13(2):201-222

Fox, J., and S. Weisberg. 2011. *An R companion to applied regression*. Sage, Thousand Oaks, CA.

Gauthier, M., and D.F. Jacobs. 2018. Ecophysiological drivers of hardwood plantation diameter growth under non-limiting light conditions. Forest Ecology and Management 419:220-226.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. Forest Science 13(1):38-53.

Graney, D.L. 1998. Ten-year growth response of red and white oak crop trees to intensity of crown release. P. 163-168 *in* Proceedings of the ninth biennial southern silvicultural research conference. General Technical Repprt SRS-20. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.

Grunwald, N.J., M. Garbelotto, E.M. Goss, K. Huengens, and S. Prospero. 2012. Emergence of the sudden oak death pathogen *Phytophthora ramorum*. Trends in Microbiology 20(3):131-138.

Hanks, L.F. 1976. Hardwood tree grades for factory lumber. Upper Darby, Pa.: U.S. Dept. of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Hatcher, J.E., T.J. Straka, and J.L. Greene. 2013. The size of forest holding/parcelization problem in forestry: A literature review. Resources 2(2):39-57.

Herbohn, J. 2006. Small-scale forestry: is it simply a smaller version of industrial (large-scale) multiple use forestry. P. 158-163 *in* Small-scale forestry and rural development: the intersection of ecosystems, economics and society. Proceedings of IUFRO 3.08 Conference, hosted by Galway-Mayo Institute of Technology, Galway, Ireland.

Holley, A., J.R. Brooks, and S.A. Moss. 2014. Converting international ¼ inch tree volume to Doyle. P. 295-298 *in* Proceedings, 19th Central Hardwood Forest Conference; 2014 March 10-12; Carbondale, IL. General Technical Report NRS-P-142. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station: 295-298.

Kenefic, L.S., M. Bataineh, J.S. Wilson, J.C. Brissette, and R.D. Nyland. 2014. Silvicultural rehabilitation of cutover mixedwood stands. Journal of Forestry 112(3):261-271.

Kentucky Division of Forestry. 2010. Kentucky Statewide Assessment of Forest Resources and Strategy.

Keyser, Chad E., comp. 2008 (revised October 2, 2019). P. 82. Southern (SN) Variant Overview: Forest Vegetation Simulator. Fort Collins, CO: US Department of Agriculture, Forest Service, Forest Management Service Center.

Lamson, N.I. 1989. Crop-tree release increases growth of 12-year-old yellow-poplar and black cherry. US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Lamson, N.I., and H.C. Smith. 1978. Response to crop-tree release: sugar maple, red oak, black cherry, and yellow-poplar saplings in a 9-year-old stand. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Lamson, N.I., H.C. Smith, A.W. Perkey, and S.M. Brock. 1990. Crown release increases growth of crop trees. Res. Pap. NE-635. Radnor, PA: US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p. 635.

Laws, J. 2018. Investment appraisal. P. 87-106 in Essentials of Financial Management. Liverpool University Press.

Lenth, R. 2018. *emmeans: Estimated marginal means, aka least-squares means. R package version 1.3.0.*

Lhotka, J.M., D.L. Parrott, and C.M. Ruffner. 2016. A Dendroecological Investigation of an Upland Oak-Dominated Forest within the Grand Prairie Region of Illinois. Natural areas journal 36(3):310-322.

Lovett, G.M., C.D. Canham, M.A. Arthur, K.C. Weathers, and R.D. Fitzhugh. 2006. Forest Ecosystem Responses to Exotic Pests and Pathogens in Eastern North America. BioScience 56(5):395-405.

McNab, W.H. 2010. Stand response of 16-year-old upland hardwood regeneration to crop-tree release on a medium quality site in the Southern Appalachians after 24 years. Res. Note SRS-18. Asheville, NC: US Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 2 p. 18.

Meadows, J.S. 1998. Growth and epicormic branching of residual trees following deferment cutting in red oak-sweetgum stands. P. 148-153 *in* Proceedings of the ninth biennial southern silvicultural research conference. General Technical Report SRS-20. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.

Mehmood, S.R., and D. Zhang. 2001. Forest parcelization in the United States: a study of contributing factors. Journal of Forestry 99(4):30-34.

Mesavage, C., and J.W. Girard. 1946. Tables for estimating board-foot volume of timber. P. 94, US Department of Agriculture, Forest Service, Washington, DC.

Miller, G.W. 1984. Releasing young hardwood crop trees: Use of a chain saw costs less than herbicides. US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Miller, G.W. 1996. Epicormic branching on central Appalachian hardwoods 10 years after deferment cutting. US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Miller, G.W. 2000. Effect of crown growing space on the development of young hardwood crop trees. Northern Journal of Applied Forestry 17(1):25-35.

Miller G.W., and J.W. Stringer. 2004. Effect of crown release on tree grade and DBH growth of white oak sawtimber in Eastern Kentucky. P. 37-44 *in* Proceedings, 14th Central Hardwood Forest Conference. 2004 March 16-19; Wooster, OH. General Technical

Report NE-316. Newtown Square, PA: US Department of Agriculture, Forest Service, Northeastern Research Station.

Miller, G.W., L.F. Hanks, and H.V. Wiant, Jr. 1986. A key for the Forest Service hardwood tree grades. Northern journal of applied forestry(1):19-22.

Morrissey, R., M. Saunders, and W. Hoover. 2011. Financial and Wildlife Benefits from Crop Tree Release in Pole-Sized Central Hardwood Oak Stands. Northern Journal of Applied Forestry 28(1):5-12.

Nadkarni, N.M., P.H. Hasbach, T. Thys, E.G. Crockett, and L. Schnacker. 2017. Impacts of nature imagery on people in severely nature-deprived environments. Frontiers in Ecology and the Environment 15(7):395-403.

Nowacki G.J., M.D. Abrams, and C.G. Lorimer. 1990. Composition, structure, and historical development of northern red oak stands along an edaphic gradient in north-central Wisconsin. Forest Science 36:276-292.

Oswalt, Oswalt M., and Roger C. Conner. 2011. Southern Forest Inventory and Analysis Volume Equation User's Guide. General Techincal Report SRS-138. US Department of Agriculture, Forest Service. Southern Research Station.

R Core Team 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Roach B.A, and S.F. Gingrich. 1968. Even-aged silviculture for upland central hardwoods. Agriculture Handbook 355. Washington D.C.: US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Schuler, T.M. 2006. Crop tree release improves competitiveness of northern red oak growing in association with black cherry. Northern Journal of Applied Forestry 23(2):77-82.

Sendak, P.E. 2008. Early crop-tree release and species cleaning in young northern hardwoods: a financial analysis. US Department of Agriculture, Forest Service, Northern Research.

Shifley, S.R., Z. Fan, J.M. Kabrick, and R.G. Jensen. 2006. Oak mortality risk factors and mortality estimation. Forest Ecology and Management 229(1-3):16-26.

Smith, H.C. 1983. Precommercial crop-tree release increases diameter growth of Appalachian hardwood saplings. US Department of Agriculture, Forest Service, Northeastern Forest Experiment.

Smith, H.C., G.W. Miller, and N.I. Lamson. 1994. Crop-tree release thinning in 65-year-old commercial cherry-maple stands (5-year results). US Department of Agriculture, Forest Service, Northeastern Forest Experiment.

Sonderman, D.L. 1987. Stem-quality changes on young, mixed upland hardwoods after crop-tree release. RP-NE 597. Broomall, PA: US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 7 p. 597.

Stringer, J.W. 1999. Development of advanced oak regeneration from two-age reserve trees. P. 291-293 *in* Proceedings, 12th Central Hardwood Forest Conference. 1999 February 28, March 1-2; Lexington, KY. General Technical Report SRS-24. Asheville, NC: US Department of Agriculture, Forest Service, Southern Research Station.

Stringer, J.W., G.W. Miller, and R.F. Wittwer. 1988. Applying a crop-tree release in small-sawtimber white oak stands.

Trimble, G.R. 1971. Early crop-tree release in even-aged stands of Appalachian hardwoods. Northeastern Forest Experiment Station.

Trimble, G.R. 1974. Response to crop-tree release by 7-year-old stems of red maple stump sprouts and northern red oak advance reproduction. US Department of Agriculture, Forest Service, Northeastern Forest Experiment.

Ward, J.S. 2002. Crop tree release increases growth of mature red oak sawtimber. Northern Journal of Applied Forestry 19(4):149-154.

Ward, J.S. 2007. Crop-tree release increases growth of black birch (Betula lenta L.) in southern New England. Northern Journal of Applied Forestry 24(2):117-122.

Ward, J.S. 2008. Crop tree release increases growth of red oak sawtimber in southern New England: 12-year results. *in* 16th Central Hardwood Forest Conference; 2008 April 8-9; West Lafayette, IN. Gen. Tech. Rep. NRS-P-24. Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station: 457-465.

Ward, J.S. 2009. Intensity of precommercial crop tree release increases diameter growth and survival of upland oaks. Canadian Journal of Forest Research 39(1):118-130.

Ward, J.S. 2013. Precommercial crop tree release increases upper canopy persistence and diameter growth of oak saplings. Northern Journal of Applied Forestry 30(4):156-163.

Ward, J.S. 2017. Twenty-five year response of non-crop trees to partial release during precommercial crop tree management. Forest Ecology and Management 387:12-18.

West, S. 2019. Kentucky Delivered Log Price Report (3rd. and 4th. Qtrs. 2019).

Wiant, H.V. 1986. Computer Corner. Northern Journal of Applied Forestry 3(3):124-124.

VITA

Philip Jay Vogel

EDUCATION

University of Kentucky, Bachelor of Science in Forestry, 2015
University of Kentucky, Minor in English, 2015

PROFESSIONAL POSITIONS

Graduate Research Assistant, University of Kentucky, 2018-2020
Horticulture Crew Foreman, LFUCG, 2017-2018