HARDWOOD REFORESTATION ON RECLAIMED MINELANDS IN THE EASTERN INTERIOR REGION: INTERACTIONS OF NURSERY STOCKTYPE, HERBICIDE, AND TREE SHELTERS ON RECLAMATION SUCCESS

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To my children, Benner Lucas and Elliot Ruth

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Thanks to my family for their absolute support in this endeavor. I am forever grateful to my partner, Regan Bailey, for her love, support, and light when times appeared dark.

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ABSTRACT

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Coal is a significant energy source for the United States and reclamation of surface mined lands is required under the Surface Mining Control and Reclamation Act of 1977. Reforestation of mined lands is challenging due to harsh conditions such as soil compaction, herbaceous competition, and animal browse. We investigated the field performance of black walnut (*Juglans nigra*), northern red oak (*Quercus rubra*), and swamp white oak (*Quercus bicolor*) planted on two mine reclamation sites and evaluated the interactions of nursery stocktypes (container and bareroot), herbicide application, and tree shelters. Survival averaged 80% across all species and stocktypes after two years. Container stocktype had greater relative height and diameter growth, whereas bareroot had greater total height and diameter growth likely due to initial stocktype differences. Shelter use increased height growth and reduced diameter growth across both stocktypes. Swamp white oak (*Q. rubra*) had high survival and field performance regardless of silvicultural treatment, whereas the two other species showed strong early regeneration responses to silvicultural treatments. Container seedlings showed promise as an alternative to bareroot seedlings to promote survival and early growth on mine reclamation sites. Future research should be on continued development of container stocktypes to provide an economically feasible mine reclamation option for land managers.

CHAPTER 1. INTRODUCTION

1.1 Surface Mining and Reclamation

In 2015, coal accounted for 28% of the United States total primary energy production (Energy Information Administration 2016), the third most important fossil fuel source. Coal extraction is accomplished either through underground or surface mining. The Eastern Interior coal region (western Kentucky, southwest Indiana and southern Illinois) is generally divided between methods with surface mining accounting for approximately 65% of coal removal in Indiana (Energy Information Administration 2016).

Surface mining is the preferred removal method when the coal deposit, or seam, is within 60 m of the surface, due to lower economic costs and higher resource recovery compared to underground mining (National Research Council 2007). There are four types of surface mining techniques with strip mining the predominant technique in the Eastern Interior region due to the relatively shallow depth of coal seams and gently rolling topography (National Research Council 2007). Strip mining consists of excavating, in a long strip, the soil and bedrock, known as overburden, above the coal seam prior to coal removal. The overburden for each successive strip is then replaced in the previous opening and may be capped with topsoil that has been stockpiled before overburden removal.

Restoration of surface mined sites is regulated through the Surface Mining Control and Reclamation Act (SMCRA) of 1977, Public Law 95-87 (US Congress 1977). SMCRA was enacted to address concerns regarding environmental problems associated with coal mining (U.S. Congress 1977). According to SMCRA, mining is considered a temporary land use, and therefore, after surface mining operations are completed, mine operators must “restore the land affected to a condition capable of supporting the uses which it was capable of supporting before any mining, or higher or better use" [Sec. 515(b)(2)]. Coalmine operators are required to submit a bond to cover the costs of reclaiming the site. Release from this bond occurs only if the land, at the end of a set time period (e.g., 3 years), meets the stated environmental conditions.

1.2 Challenges for Reforestation of Mined Lands

Requirements of SMCRA have resulted in the widespread adoption of reclamation techniques that often result in adverse conditions for reclamation with trees, through establishment of aggressive ground cover species, intensive grading, and compaction of replaced topsoil materials (Chaney et al. 1995; Ashby 1996, 1999; Franklin et al. 2012). Mine operators must return sites to their approximate original contour, and mine spoils are typically heavily graded and compacted. Where topsoil is not available topsoil substitutes may have poor physical and chemical properties, which fail to promote tree growth (Andersen et al. 1989; Scullion and Malinovszky 1995; Rodrigue and Burger 2004). As a result, performance of forest trees planted on post-SMCRA reclaimed mines is often deficient compared with those growing in native forest sites or other afforestation settings (Probert 1992; Torbert and Burger 2000). Many sites in the eastern U.S. reclaimed after the initiation of SMCRA were therefore established as grasslands, wildlife habitat (grasslands with a mix of woody wildlife food plants), or unmanaged forest (ground cover grasses with a mix of black locust, pine species, and woody shrubs) , which currently have limited economic value, rather than native hardwood forests (Burger et al. 2005; Groninger et al. 2006).

Despite the challenges under SMCRA, proper engineering and operational procedures to reclaim and prepare mine soils for forestry uses combined with an understanding of silvicultural practices to improve tree establishment and growth on these sites can yield productive forests at similar costs to other post-mining uses (e.g., pasture, wildlife habitat) (Burger et al. 2002; Zipper et al. 2011) with productivity at least equal to native forests removed by mining (Rodrigue and Burger 2004). Beyond traditional values such as wildlife, recreation, biodiversity, and economic benefits, forests also possess other ecosystem values important to reclaiming mined sites including enhancing and protecting soils, restoring soil organism populations and associated nutrient cycling functions, regulating quality water yields, groundwater recharge, flood protection, controlling erosion and filtering runoff, moderating climatic extremes, reducing air pollution, and carbon sequestration (Ashby and Vogel 1993).

Sites that were mined before the introduction of SMCRA are termed Abandoned Mine Lands (AMLs). While some of these sites have been successfully reclaimed into forestlands that are as productive as un-mined counterparts (Rodrigue et al. 2002), many AML sites are still in need of reforestation. The benefits of restoring these sites, such as improvements to hydrological processes, decreased erosion and sediment flow (Olyphant and Harper 1995), increased area of forest cover, and provision of productive timber lands has led the Office of Surface Mining Reclamation and Enforcement (OSMRE) to promote reclamation of AMLs, with funds provided through SMCRA. While AML sites were not subject to the same requirements as post-SMCRA sites, establishment of forest cover is still often difficult due to poor soil physical and chemical characteristics, as well as microsite variability associated with mixed spoil.

1.3 Site specific limiting factors

The main abiotic and biotic factors that limit early establishment success of newly planted seedlings on mine reclamation sites in the eastern U.S. include soil compaction (Ashby and Vogel 1993; Bateman and Chanasyk 2001; Skousen et al. 2009; Fields-Johnson et al. 2014), competition from weeds (Ashby 1997; Casselman et al. 2006; Skousen et al. 2009; Franklin et al.

2012), animal browse (Stange and Shea 1998; Tripler et al. 2002; Casabon and Pothier 2007; Hackworth and Springer 2018), and low soil fertility (Bussler et al. 1984; Andersen et al. 1989).

Individually or in combination these factors create conditions difficult for tree seedlings to couple to the site after planting. Therefore, it is important to understand site limitations in order to prescribe optimal silvicultural treatments to increase successful restoration of post mined sites. Limiting factors are additive and ordered, which means once one factor is minimized then another factor will likely become limiting (Landis 2011). Hence, restoration managers have access to many silvicultural treatments that can mitigate more than one limiting factor, but costs and project objectives dictate which treatments are selected for a given site.

1.4 Nursery Stocktypes

In the eastern US, bareroot oak seedlings are the most common nursery stocktype (Dey et al. 2008), partly associated with low production costs. However, fine root loss and/or desiccation during lifting, storage, and transport may lead to water stress, reduced leaf area (Struve and Joly 1992; Jacobs et al. 2009), and shoot dieback (Johnson et al. 1984; Wilson et al. 2007) following planting of bareroot seedlings, especially under stressful conditions of mine reclamation sites. Container seedlings represent an alternative to bareroot production that may improve field establishment success of hardwoods (Wilson et al. 2007; Woolery and Jacobs 2014). Following nursery lifting, container seedlings tend to be smaller than bareroot seedlings (Wilson et al. 2007; Dey et al. 2008) though they often have a greater root-to-shoot ratio. Additionally, because root systems remain intact and surrounded by media at lifting, container seedlings typically show greater root proliferation and reduced transplanting stress (McKay 1997; Grossnickle 2005; Grossnickle and El-Kassaby 2016). For example, container northern red oak (*Quercus rubra*) seedlings have consistently been reported to have reduced transplant stress and greater relative growth rates than bareroot seedlings across a variety of regeneration sites in the eastern US (Johnson et al. 1984; Zaczek et al. 1997; Wilson et al. 2007; Woolery and Jacobs 2014).

Although somewhat higher costs have limited use of container seedlings for hardwood regeneration on many sites in the eastern US (Dey et al. 2008), the added investment may be justified on mine reclamation sites if seedlings are better able to withstand typical post-planting stresses that occur on these sites such as drought, poor site nutrition, and animal herbivory. Browsing (i.e., deer and rabbit/vole) can be particularly damaging on many mine reclamation sites and because browsing inhibits new root growth (Ruess et al. 1998), the improved water status and greater root absorptive capacity of container seedlings following transplant that is commonly observed may reduce negative effects of browsing stress on seedling establishment (Grossnickle 2005; Woolery and Jacobs 2011).

Despite the potential for container seedlings to improve mine reclamation success, relatively little research has examined the influence of nursery stocktypes on seedling establishment during reclamation, particularly in the Midwest. Davis and Jacobs (2004) evaluated performance of container (June-sown and January-sown) and bareroot (standard-density, 75 seedlings/m^2 or low-density, 21 seedlings/m^2) seedlings planted onto AML and post-SMCRA sites in southwestern Indiana and found that container seedlings were significantly less drought stressed during the summer following planting, thus indicating their performance potential.

1.5 Browse Protection

Damage from browse is a major limiting factor to post-planting seedling establishment success. Browse impairs basic plant physiological processes (e.g. CO_2 assimilation, respiration, synthesis of sugars and proteins) and alters plant growth patterns that directly impact seedling performance. Repeated and heavy browse may reduce seedling growth and increase mortality. In Indiana, white-tailed deer (*Odocoileus virginianus*) damage often causes plantation failure (Jacobs et al. 2004). Therefore, plantation establishment benefits from browse protection until seedlings grow above the browse line or are of sufficient size that browse minimally impacts growth. Current operational browse protection measures include fencing and tree shelters.

Fencing is effective in excluding large herbivores during the critical first 5-8 years of plantation establishment. Results from a study in Pennsylvania investigating fencing and lime addition determined that fencing was the only significant factor increasing height growth response of northern red oak (Long et al. 2012). Fencing increased first year survival and height growth of white oak and black locust seedlings through reduced herbivory on several Appalachian mine reclamation sites (Hackworth and Springer 2018). Similarly, fencing improved growth rates for black cherry, bur oak, and white oak on reclaimed mine land in southwestern Indiana (Burney and Jacobs 2018). The effectiveness of fencing, however, is limited to exclusion of large herbivores; on sites in which small mammals or rodents may be a greater limiting factor, alternatives to fencing are required, such as tree shelters.

Tree shelters, or tubes, have been used since the late 1970's and are generally open-ended, vented cylinders of various heights, diameters, and translucent plastic material in which seedlings grow (Tuley 1985; Potter 1988). Shelters were originally designed to protect against browse damage from large herbivores (Potter 1988), with an unintended benefit of protection from smaller mammals and rodents, allowing seedlings to reach a free-to-grow state. Additionally, shelters have been found to promote survival and height growth while also altering the microclimate, light, diameter and root to shoot (R/S) ratio of seedlings as detailed below.

Studies have frequently shown that shelters increase survival and height growth in the early phase of hardwood seedling establishment (Stange and Shea 1998; Dubois et al. 2000;

Ponder 2003; Taylor et al. 2006; Valkonen 2008; Andrews et al. 2010; Mariotti et al. 2015; Hackworth and Springer 2018) and similar results were found for direct seeded American chestnut (*Castanea dentata*) planted on an Appalachian mine reclamation site (Barton et al. 2015). Common to all these studies is that shelters prevent browse damage and promote height growth, thereby improving seedling establishment.

Alteration of the microclimate (i.e., increased air temperatures and relative humidity) inside tree shelters is a well-documented phenomenon (Kjelgren and Rupp 1997; Sharew and Hairston-Strang 2005; Oliet and Jacobs 2007; Mechergui et al. 2013). These simulated greenhouse conditions are thought to lengthen the growing season for seedlings thereby promoting greater height growth. However, there is also the potential for reduction in seedling vigor and cold tolerance to cause dieback and mortality (Kjelgren et al. 1997).

Seedling growth response within shelters depends upon species-specific growth patterns as shelters alter light quality and transmission. Species that exhibit slow early growth, such as those in the genus *Quercus*, tend to respond positively to shelter use as compared to species that prioritize a rapid early growth pattern, such as *Juglans* (Ponder 2003; Andrews et al. 2010; Mariotti et al. 2015). A comparison of different tree shelters indicated that greater light transmission and a red:far red ratio closer to open canopy forest promoted greater height growth for various hardwood species (Sharew and Hairston-Strang 2005). However, diameter growth does not follow the same pattern and is neutrally or negatively related to shelter use as seedlings allocate resources toward greater height growth to reach available light (Jacobs 2011; Mechergui et al. 2013; Oliet et al. 2016).

Tree shelters have been linked to reduced diameter growth and alteration of the seedling root:shoot (R/S) ratio, which may have important implications for seedling establishment, particularly on harsh mine reclamation sites. Such difficult site conditions favor seedlings that have a greater R/S ratio, or more balanced growth, improving successful coupling to the site (Grossnickle 2012). In a study of shelter effects on shoot and root system growth of *Q. robur*, researchers found that shelters reduced root system development and R/S ratio with greater biomass allocated above ground as compared to non-sheltered seedlings (Mariotti et al. 2015). In contrast, Mechergui et al. (2013) using *Q. suber*, found reduced root biomass but no difference in R/S ratio between sheltered and unsheltered seedlings.

There have been several studies investigating shelter effects on seedlings planted on reclaimed mine sites, but most study locations were in the Appalachian coal region. In a recent study, first-year seedling survival was significantly improved with shelters for black locust and white oak, but not for short leaf pine on several sites in eastern Kentucky (Hackworth and Springer 2018). There was no significant difference in height between the sheltered and unsheltered treatments and no significant interaction of species and shelter treatment. A West Virginia study found survival of chestnut (*Castanea* spp.) trees grown with shelters had better survival and greater height growth after 8 years (Skousen et al. 2018). Another Kentucky study found that shelters increased germination rate and survival of direct seeded chestnut compared to unsheltered seeds (Barton et al. 2015), which was attributed to protection from seed predation by rodents in the sheltered treatment.

1.6 Species Selection

Spanning eastward from Missouri to West Virginia and south from Wisconsin to Alabama, the central hardwood forest region (CHFR) is mainly dominated by oak-hickory forests (Fralish 2003). Geographic variability within this region ranges from unglaciated mountains to formerly glaciated lowlands. As a result, there is a diverse suite of hardwood species that occur natively, and which are available from nurseries for outplanting in reforestation efforts. The high diversity of hardwoods species provides an opportunity for selective use of species matched to specific sites and management objectives. This differentiates mine reclamation efforts in the Eastern Interior Region from other mining areas in the US and the world where limited species choices are available. For example, the boreal zone has a limited selection of conifers in the genus *Picea* and *Pinus* along with aspen (*Populus* spp.), which are predominately used in mine reclamation efforts (Sloan and Jacobs 2013; Hankin et al. 2015; Sloan et al. 2016). Whereas in the Appalachian Region, hardwood species used are similar, but the use of various conifers (Torbert et al. 1990, 1995; Casselman et al. 2006; Fields-Johnson et al. 2014) is distinct due to native range of most conifers falling outside the Eastern Interior coal basin.

Performance of hardwood species on reclaimed mine sites in the Easter Interior Region is highly variable. Major species planted include: ash (*Fraxinus americana* and *F. pennsylvanica*), black cherry (*Prunus serotina*), black locust (*Robinia psuedoacacia*), black walnut (*Juglan nigra*), hickory (*Carya spp*), oaks (*Quercus alba, Q. velutina, Q. rubra, Q. macrocarpa, Q. bicolor*), and tulip poplar (*Liriodendron tulipifera*) (Andersen et al. 1989; Ashby 1996; Davis and Jacobs 2004; Groninger et al. 2006; Johnston et al. 2012). Ash (*Fraxinus spp*) is no longer planted as it is almost extirpated by the emerald ash borer. Of the remaining species, black cherry, black walnut, and oaks comprise the majority of reclamation plantings in the Eastern Interior Region (Andersen et al. 1989; Chaney et al. 1995; Jacobs et al. 2009; Salifu et al. 2009; Johnston et al. 2012; Burney and Jacobs 2018).

In a study investigating mowing and soil ripping on a West Virginia mine site with black cherry, black walnut, white ash, tulip-poplar, and red oak, Skousen et al. (2009) found variable seven-year survival and growth responses among the species. While first year survival was around 80%, after seven years average survival for black cherry was 36%, red oak 47%, tulip poplar 66%, and black walnut 80%. In the same study, tulip poplar had the greatest mean growth followed by black walnut, black cherry, and red oak had the lowest growth after seven years. Another West Virginia study found red oak and white oak height averaged 200 cm, while tulip poplar averaged 400 cm after 8 years on two mine reclamation sites (Dallaire et al. 2015). In an Indiana study investigating fertilization and fencing on three species of oaks (bur, red and white) and black cherry planted onto a reclaimed mine site, Burney and Jacobs (2018) found species-specific responses in survival and growth after 2 years. Red oak had the lowest survival compared to the other species regardless of treatment. Black cherry had the greatest height and white oak had the smallest final height, attributed to initial height differences; however, white oak had the greatest height gain with fencing regardless of fertilizer treatment. Black cherry had the largest final diameter with fencing and highest fertilization rate, while bur oak and white oak responded similarly to the same treatment combination with larger final diameter as compared to no fertilization.

Hardwood species have wide variation in ecology, which can be used to match specific species to the limiting site factors found on mine reclamation sites. Through targeting species, land managers can utilize other silvicultural techniques, such as alternate stocktypes, site preparation, fertilization, and browse control to improve mine reclamation success in the eastern U.S. and Eastern Interior Region. However, despite the demonstrated potential from other regions to select alternate nursery stocktypes that effectively account for site limiting factors according to the Target Plant Concept (Landis 2011), little research has examined the effects of using varying nursery stocktypes on reclamation success in Indiana.

1.7 Objectives and Hypotheses

I conducted a comprehensive analysis of the effects of nursery stocktypes (bareroot vs. container seedlings) on mine reclamation plantings in southern Indiana. Specific objectives for this project were accomplished in a two-year field study. The field study assessed the stress resistance and overall field performance of container (0 + 1) seedlings to that of traditional bareroot (1 + 0) seedlings for three hardwood tree species planted on two mine reclamation sites and evaluated the interactions of two different nursery stocktypes with two levels of herbicide and tree shelter use. Hypotheses include (*a*) container stocktype will have better survival, drought stress resistance, and growth than bareroot stocktype, in part due to more fibrous root system development and higher root:shoot ratios; (*b*) herbicide treatment will more positively benefit bareroot stocktype because the expected lower root:shoot ratio of this stocktype will have greater transplant stress and cause these seedlings to be more susceptible to competition for moisture and nutrients (*c*) the smaller size of container seedlings (contained mainly within the shelters) will result in greater growth of these seedlings relative to bareroot seedlings due to greater utilization of the greenhouse conditions caused by shelters.

CHAPTER 2. INTERACTIONS OF NURSERY STOCKTYPE, HERBICIDE, AND TREE SHELTERS ON RECLAMATION SUCCESS

2.1 Introduction

In 2015, coal accounted for 28% of the United States total primary energy production (Energy Information Administration 2016), the third most important fossil fuel source. Surface mining is the preferred removal method when the coal deposit, or seam, is within 60 m of the surface, due to lower economic costs and higher resource recovery compared to underground mining (National Research Council 2007). Strip mining consists of excavating, in a long strip, the soil and bedrock, known as overburden, above the coal seam prior to coal removal. During subsequent mine reclamation, the overburden for each successive strip is then replaced in the previous opening and may be capped with topsoil that has been stockpiled before overburden removal.

The Surface Mining Control and Reclamation Act (SMCRA) of 1977 (Public law 87-95) was enacted to address concerns regarding environmental problems associated with coal mining (US Congress 1977). According to SMCRA, mining is considered a temporary land use, therefore, after surface mining operations are complete, land must be returned to a condition capable of supporting its pre-mining land cover (Torbert and Burger 2000). Mine operators are required to submit a bond to cover the costs of reclaiming the site. Bond release occurs only if the land, at the end of a set time period (e.g., 5 years), meets the stated environmental conditions (Torbert and Burger 2000).

Requirements of SMCRA, have resulted in widespread adoption of reclamation techniques that often create adverse conditions for reclamation with trees, including establishment of aggressive ground cover species, intensive grading, and compaction of replaced topsoil materials (Chaney et al. 1995; Ashby 1996, 1999; Franklin et al. 2012). Mine operators must return sites to approximate original contour, therefore mine spoils are typically heavily graded and compacted to meet this criterion. Topsoil substitutes tend to have poor physical and chemical properties, which inhibit tree growth (Andersen et al. 1989; Scullion and Malinovszky 1995; Rodrigue and Burger 2004).

Performance of trees planted on reclaimed mines is thus often deficient compared with trees growing in native forest sites or other afforestation settings (Probert 1992; Torbert and Burger 2000). Many sites in the eastern U.S. reclaimed after the initiation of SMCRA were established as grasslands, wildlife habitat (grasslands with a mix of woody wildlife forage), or unmanaged forest (ground cover grasses with a mix of black locust, pine species, and woody shrubs) rather than native hardwood forests, and currently have limited economic value (Torbert and Burger 2000; Burger et al. 2005; Groninger et al. 2006). Despite challenges under SMCRA, proper engineering and operational procedures to reclaim and prepare mine soils for forestry uses combined with an understanding of silvicultural practices to improve tree establishment and growth on these sites can yield productive forests at similar costs to other post-mining uses (e.g., pasture, wildlife habitat) (Burger et al. 2002; Zipper et al. 2011) with productivity at least equal to native forests removed by mining (Rodrigue and Burger 2004). Beyond traditional values such as wildlife, recreation, biodiversity, and economic benefits, forests also possess other ecosystem functions important to reclaiming mined sites including enhancing and protecting soils, restoring soil organism populations and associated nutrient cycling functions, regulating quality water yields, groundwater recharge, flood protection, controlling erosion and filtering runoff, moderating climatic extremes, reducing air pollution, and carbon sequestration (Ashby and Vogel 1993).

Sites that were mined before the introduction of SMCRA are termed Abandoned Mine Lands (AMLs); although some AMLs have been successfully reclaimed into productive forestlands (Rodrigue et al. 2002), many AML site are still in need of reforestation. The benefits of restoring these sites, such as improvements to hydrological processes, decreased erosion and sediment flow (Olyphant and Harper 1995), increased area of forest cover, and provision of productive timber lands has led the Office of Surface Mining Reclamation and Enforcement (OSMRE) to promote reclamation of AMLs, with funds provided through SMCRA. While AML sites were not subject to the same requirements as post-SMCRA sites, establishment of forest cover is still difficult due to poor soil physical and chemical characteristics, as well as microsite variability associated with mine spoils.

Main abiotic and biotic factors that limit early establishment success of newly planted seedlings on mine reclamation sites in the eastern U.S. include low soil fertility (Bussler et al. 1984; Andersen et al. 1989), soil compaction (Ashby and Vogel 1993; Bateman and Chanasyk 2001; Skousen et al. 2009; Fields-Johnson et al. 2014), competition from weeds (Ashby 1997; Casselman et al. 2006; Skousen et al. 2009; Franklin et al. 2012), and animal browse (Stange and Shea 1998; Tripler et al. 2002; Burney and Jacobs 2018; Hackworth and Springer 2018). Through cooperation and partnerships between research and operation, significant progress has been made in identifying silvicultural treatments to overcome these challenges. For example, the Appalachian Regional Reforestation Initiative (www.arri.ormre.gov) has developed a Forestry Reclamation Approach to reclaim coal-mined lands that provides specific, scientifically derived recommendations for rooting medium, ground covers, tree species selection, and tree planting techniques.

Reforestation efforts utilize bareroot or container stocktypes. In the eastern US, bareroot seedlings are the most common planting stocktype (Dey et al. 2008), partly associated with low production costs. However, fine root loss and/or desiccation during lifting, storage, and transport may lead to water stress, reduced leaf area (Struve and Joly 1992; Jacobs et al. 2009), and shoot dieback (Johnson et al. 1984; Wilson et al. 2007) following planting of bareroot seedlings particularly under stressful conditions of mine reclamation sites. Container seedlings represent an alternative to bareroot production that may improve field establishment success of hardwoods (Woolery and Jacobs 2014). Following nursery lifting, container seedlings tend to be smaller than bareroot seedlings (Wilson et al. 2007; Dey et al. 2008) though they often have a greater root-to-shoot ratio. Additionally, because root systems remain intact and surrounded by media at lifting, container seedlings typically show greater root proliferation and reduced transplanting stress (McKay 1997; Grossnickle 2005; Grossnickle and El-Kassaby 2016). For example, container northern red oak (*Quercus rubra* L.) seedlings have consistently demonstrated reduced transplant stress and greater relative growth rates than bareroot seedlings across a variety of regeneration sites in the eastern US (Johnson et al. 1984; Zaczek et al. 1997; Wilson et al. 2007; Woolery and Jacobs 2014).

Although higher costs have limited use of container seedlings for hardwood regeneration on many sites in the eastern US (Dey et al. 2008), the added investment may be justified on mine reclamation sites if seedlings can better withstand typical post-planting stresses that occur on these sites such drought, poor site nutrition, and animal herbivory. Browsing (i.e., deer, rabbit, and vole) can be particularly damaging on mine reclamation sites and because browsing inhibits new root growth (Ruess et al. 1998). Improved water status and greater root absorptive capacity of container seedlings following transplant may reduce negative effects of browsing stress on seedling establishment (Grossnickle 2005; Woolery and Jacobs 2011).

Despite the potential for container seedlings to improve mine reclamation success, relatively little research has examined the influence of nursery stocktypes on seedling establishment for mine reclamation, particularly in the Midwest. Davis and Jacobs (2004) evaluated performance of container and bareroot seedlings planted onto AML and post-SMCRA sites in Indiana and found that container seedlings were significantly less drought stressed during the summer following planting, thus indicating container seedling performance potential.

Our field study assessed the stress resistance and overall field performance of container (0 + 1) seedlings to that of traditional bareroot (1 + 0) seedlings for three hardwood tree species planted on two mine reclamation sites and evaluated the interactions of two different nursery stocktypes with two levels of herbicide and shelter use. Objectives of this study were accomplished in a two-year field study where specific hypotheses included:

(*a*) container stocktype will have better survival, drought stress resistance, and growth than bareroot stocktype, due to more fibrous root system development and higher root:shoot ratios;

(*b*) herbicide treatment will more positively benefit bareroot stocktype compared to container seedlings because the expected lower root:shoot ratio of this stocktype will have greater transplant stress and cause these seedlings to be more susceptible to competition for moisture and nutrients;

(*c*) the smaller size of container seedlings (contained mainly within the shelters) will result in greater growth of these seedlings relative to bareroot seedlings due to greater utilization of the greenhouse conditions caused by shelters.

2.2 Material and Methods

2.2.1 Study Sites

This study was established on two sites in Greene and Sullivan Counties, near Dugger, IN, USA: (*a*) CR400 (39°01' N, 87°15’ W) is approximately 6 km south of the town of Dugger and (*b*) Dugger (39°03' N, 87°21' W) is approximately 10 km west-southwest of the town of Dugger. Sites were selected for reclamation history and relative proximity to each other. CR400, last mined in the 1950's and considered an AML site, was reclaimed in 2013 to mitigate the hazard of a highwall and water filled pit along a county road. The reclamation method consisted of grading and "loosely" compacting the overburden, with a slope < 25%, no topsoil was added, and seeded with a current operational mixture of grasses and legumes used by the Indiana Department of Natural Resources Division of Reclamation. Primary species in this seeding mix were Korean lespedeza (*Kummerowia stipulacea*), red clover (*Trifolium pratense*), perennial ryegrass (*Lolium perenne*), orchard grass (*Dactylis glomerata*), and switchgrass (*Panicum virgatum*).

The Dugger site, owned and operated by Peabody Coal Company until 1985, was reclaimed in 1996 using post-SMCRA techniques. This method involved heavily grading and compacting the overburden material prior to placing a variable depth of topsoil (20-45 cm), again graded and compacted, before seeding with a mixture of aggressive grasses and legumes consisting of sericea lespedeza (*Lespedeza cunata*), goldenrod (*Solidago virgaurea*), ragweed (*Ambrosia artemisiifolia*), and foxtail barley (*Hordeum jubatum*) (Salifu et al. 2009; Burney and Jacobs 2018). Additionally, each site had 2.5-m tall polypropylene mesh deer fence surrounding the approximately 1 ha planting sites.

2.2.2 Plant Material

Swamp white oak (*Quercus bicolor*), northern red oak (*Q. rubra*), and black walnut (*Juglans nigra*) were selected based on commercial/wildlife value and because they have performed relatively well (swamp white oak) or inconsistently (northern red oak and black walnut) in Indiana mine reclamation. Two nursery stocktype treatments were used. The first stocktype was one-year-old bareroot seedlings (1+0) grown under standard nursery cultural practices at the Indiana Department of Natural Resources (IDNR) State Tree Nursery near Vallonia, IN, (38°85' N, 86°10' W). After lifting, grading, and packing in mid-January 2016, seedlings were transported to the Purdue University, John S. Wright Forestry Center (40°26’ N, 87°02’ W) and stored at approximately 4°C until planting in mid-April 2016. The second stocktype, container seedlings (0+1), were grown at Woody Warehouse nursery in Lizton, IN (39°53’ N, 86°35’ W). Containers were made of fiber cloth with no bottom and approximate volume of 580 cm^3. This container size provided an excellent cost-performance balance because the seedlings can be grown to be cost competitive with bareroot stock and machine planted (Dey et al. 2008). After hardening in mid-November 2015, seedlings were transported to the Purdue University John S. Wright Forestry Center and stored at approximately 4°C until planting in mid-April 2016.

2.2.3 Herbicide Treatments

In late October 2015, only the Dugger site received mechanical site preparation, which consisted of mowing using a 33 horsepower Kubota tractor with a John Deere MX5 rotary cutter set at the lowest level (8-cm). This was to remove the approximately 1-m tall vegetation present and ease planting site layout, which was not an issue at CR400. Additionally, both CR400 and Dugger were mowed, between rows, twice in 2016 and once during the 2017 growing seasons prior to data collection.

On 17 May 2016 each planting site was treated with the first herbicide treatment using a mixture of Pendulum AquaCap (BASF, active ingredient pendimethalin – 38.7%), a pre-emergent for grasses and broadleaf weeds (3.9 L/ha) and Clethodium PS (Albaugh, Inc., active ingredient clethodium – 26.4%), a grass specific post-emergent (0.71 L/ha). Application was via tractor-mounted sprayer in approximately 1-m band centered on the planted row.

Each site received the second year of weed control on 21 March 2017. Trees were dormant at this time and a mixture of Pendulum AquaCap (BASF, 2.9 L/ha), RoundUp (Monsanto, active ingredient glyphosate – 48.7%), a broad-spectrum systemic herbicide for grass and annual broadleaf weeds (0.95 L/ha), and Oust (Bayer, active ingredient sulfometuron methyl – 75%), control of annual/perennial grasses and broadleaf weeds (0.03 L/ha) was used. Application was via 19-L backpack sprayer to planted rows in approximately 1-m width.

2.2.4 Browse Treatments

Browsing treatments consisted of either no browse protection or browse protection using 30-cm tall x 15-cm diameter, white plastic, vented, tree shelter tubes (Miracle Tube, Tree Pro, West Lafayette, IN) to exclude damage from rabbits and voles.

2.2.5 Machine Planting Method

CR400 and Dugger sites, in that order, were machine planted over two consecutive days in mid-April 2016 using the Wright-MSU machine planting method (McKenna et al. 2011). A Whitfield '88-2N' machine planter pulled by a John Deere 6410, 100 horsepower tractor was used. The machine planter has a 66-cm coulter wheel followed by a 5-cm trencher foot that opens the ground as the tractor moves forward. Tree seedlings are placed in the trencher opening and two packing wheels at the end of the unit seal the ground to set the trees. The same tractor operator and planter were used at each site. Sites were planted at 2.4-m by 1.2-m spacing. Between row spacing was 2.4-m and seedlings planted at 1.2-m intervals within rows.

2.2.6 Experimental Design

The experimental design was a split-split, nested design with a 3 × 2 × 2 × 2 factorial treatment structure (Figure 2.1). This included species at 3 levels (e.g., swamp white oak, northern red oak, and black walnut), herbicide at 2 levels (1 or 2 years), stocktype at 2 levels (bareroot or container seedlings), and browse at 2 levels (tree shelter or none).

In the field, plots were designated according to herbicide treatment. Within each of these whole plots, sub-plots were established for each of the three species. In each sub-plot, nursery stocktype and browse treatments were nested; treatments were randomly assigned to rows with each treatment combination represented (20 seedlings × 3 species × 2 herbicide treatments × 2 stocktypes × 2 browse treatments × 2 sites × 3 replicates). Thus, there were a total of 2880 seedlings planted.

2.2.7 Measurement Variables

Initial seedling status - Prior to planting, a sub-sample of 12 seedlings from each nursery stocktype (bareroot or container) and species were destructively sampled to evaluate initial seedling morphology to characterize initial seedling quality. Seedlings were measured for initial height (from root collar to base of apical bud) and root collar diameter (RCD). Roots were carefully washed to remove growing medium. Shoots were separated from roots at the root collar and placed into individual labeled paper bags. Samples were dried for 72 hours at 70°C, then weighed to the nearest 0.10 gram for dry mass determination. Root to shoot ratios were calculated by dividing root dry mass by shoot dry mass.

Evaluation of seedling development - Seedlings were presorted prior to planting to ensure that browsed, damaged, or abnormally small or large seedlings were removed to minimize potential confounding effects from nursery to field. Field measurements including initial ground line diameter (GLD) and height to last live apical bud were collected on 7 July 2016. Height, GLD, survival, and browse data were recorded over several days in mid-November 2016 and again over several days in mid-November of 2017. Height was measured to the nearest 0.5 cm; GLD was measured using calipers to the nearest 0.1 mm. Relative height and diameter growth were calculated from field measurements by taking the absolute height or diameter for specific time periods relative to initial height or diameter of seedling (i.e., absolute height/initial height).

Pre-dawn leaf water potential - Pre-dawn leaf water potential was measured on three randomly selected seedlings per nested treatments, within each of the 3 species sub-plots at both sites, over one night of October 5-6, 2016, during a typical late season drought period (i.e., at least 7 days since the last rain event). Pre-dawn leaf water potential is used in determining chronic water stress of a plant and as a proxy for soil water (Pallardy et al. 1991). A Scholander pressure chamber (Model 1000, PMS Instruments, Corvallis, OR) was used to take pressure measurements. A 10× magnification hand lens was utilized to view the leaf petiole and pressure was recorded at the point when xylem water was expressed from the petiole.

Browse assessment - Browse assessments occurred during field measurements in each growing season. Browsing damage was identified as deer, rabbit, or vole according to a visual inspection of the damage. Deer remove the shoot terminal buds and leave ragged edges. Rabbit herbivory is indicated by clean, angled shoot removal. Bark removal near the base is considered vole damage (Hackworth and Springer 2018).

Soil characteristics - Soils were sampled from each site in April 2017 to determine organic matter; pH; bulk density; cation exchange capacity (CEC); total phosphorous, potassium, magnesium, and calcium; carbon:nitrogen ratio; and texture. In each plot, twelve soil cores, approximately 20 cm × 3 cm, were collected along two transects perpendicular to planted rows and then bulked, thus there were six composite samples per site. Composite samples were sent to A&L Great Lakes Laboratory, Inc. (Fort Wayne, IL, USA) for analysis.

2.2.8 Statistical Analysis

Morphological data were analyzed using analysis of variance (ANOVA) with linear mixed models (lmer) in the 'lme4' package (Bates et al. 2015) for R (RStudio Team, Boston, MA, USA). Data was analyzed independently for each species. Fixed effects were site (CR400 or Dugger), stocktype, shelter, and herbicide with block as the random effect. The Kenward-Roger option was used in the 'lmerTest' package for R to adjust denominator degrees of freedom and obtain *p* values for ANOVA tests (Kuznetsova et al. 2017). When treatment differences were found, the 'lsmeans' package in R (Lenth 2016) was used to perform post-hoc pairwise comparison of least squares means. Survival data were analyzed similarly to morphological data except generalized linear mixed models (glmer), using the binomial family, in the 'lme4' package for R were used. The highest interactions between treatments were two-way as the models would not converge with three-way interactions. Leaf water potential data were analyzed using ANOVA with general linear models (glm). The 'lsmeans' package in R was used to perform post-hoc pairwise comparisons for all treatment differences found to be significant. All data were checked for normality, homoscedasticity, and data was transformed if required to satisfy model assumptions. The significance level for all tests performed was $\alpha = 0.05$.

2.3 Results

2.3.1 Pre-Planting

There were pre-planting stocktype differences for all species. Bareroot stocktype was significantly taller than container stocktype (Table 2.1). The stocktype trend was similar for root collar diameter except in swamp white oak where there was no significant difference between the stocktypes. Root and shoot dry weights followed the same trend with bareroot stocktype having greater root and shoot dry weights for all species. However, only black walnut had a significantly different root:shoot ratio (Table 2.1).

2.3.2 Browse

After two years, the total number of seedlings browsed by deer, rabbits, or voles was very low, i.e., 81 out of 2880 seedlings (2.81%) which did not vary by treatment (Appendix Table A.1).

2.3.3 Soils

There were several significant differences in edaphic properties between the two planting sites (Table 2.2). CR400 had significantly greater percent organic matter (3.2%) compared to Dugger (2.8%). Additionally, CR400 had double the cation exchange capacity, phosphorous, calcium, and carbon to nitrogen ratio as the Dugger site.

2.3.4 Survival

Overall survival at the end of the first growing season averaged 93% across all species. Survival among species was black walnut (90%), red oak (92%) and swamp white oak (99%). Several statistically significant treatment effects and interactions were detected for black walnut survival (Table 2.3). Shelter use had opposite effects on first year survival of black walnut stocktypes (stocktype × shelter, $p = 0.0031$) with shelters improving survival for bareroot (99%) and reducing survival for container seedlings (82%). A first-year survival site × stocktype interaction was detected for red oak ($p = 0.0468$, Table 2.3), but pairwise comparison of least squares means indicated no difference in survival. No treatments had a significant effect on swamp white oak first year survival (Table 2.3).

Second year survival averaged 86% across all species with black walnut (85%), red oak (77%) and swamp white oak (97%). All species had significant treatment interactions for two-year survival (Table 2.3). Black walnut had a significant site × herbicide interaction ($p < 0.0001$) where only at CR400 two years of herbicide improved survival (97%) compared to one year of herbicide (81%). Black walnut also had a stocktype × shelter interaction ($p = 0.0011$) where only bareroot with shelter had the greatest survival (95%) compared to bareroot without shelter (83%) and container irrespective of shelter treatment (81%). Additionally, red oak had a similar stocktype × shelter interaction ($p = 0.0179$) where survival with shelter was significantly greater only for bareroot (90%) compared to bareroot without shelter (80%), and container regardless of shelter treatment (79%, Figure 2.2). A site × stocktype interaction was detected for red oak (p = 0.0009, Table 2.3), where container stocktype planted at CR400 had greater survival (92%) than bareroot (81%) or both stocktypes at the Dugger site (average of 68%). Swamp white oak had a marginally significant site × shelter interaction (p = 0.0439), however the pairwise comparison of least squares means indicated no significant differences for the interaction. A significant stocktype × herbicide interaction (p = 0.0090, Table 2.3) was found for swamp white oak with survival of container stocktype having two years of herbicide (94%) significantly lower than bareroot with two years (99%) but similar to bareroot or container with one year of herbicide (average of 96%).

2.3.5 Height and Diameter Growth

Stocktype had a significant influence on growth for all species with container stock having greater relative height and diameter growth than bareroot stock. Higher level interactions varied among species for relative growth (Tables 2.4 and 2.5).

Stocktype × shelter interaction was detected for first year relative height growth of black walnut (p < 0.0001) and red oak (p = 0.0034) but not swamp white oak (Table 2.4). The same interaction for first year relative diameter growth was found for red oak (p = 0.0438) and swamp white oak (p = 0.0056) but not black walnut (Table 2.5). Height and diameter growth were greater for container stocktype compared to bareroot with shelter significantly improving height growth in black walnut and red oak (Figure 2.3). Shelter had an opposite effect on diameter growth where sheltered container black walnut and red oak showed a significant difference through reduced diameter growth. However, swamp white oak had no significant diameter growth difference for either stocktype. While not significant, sheltered 1-year-old container swamp white oak mean GLD growth was greater than not sheltered (Figure 2.4).

All species had significant interactions of site × stocktype for second year relative height growth (Table 2.4). Container stock had significantly greater growth than bareroot for all species with no site differences between bareroot stocktypes of black walnut and red oak but significant differences for swamp white oak (Figure 2.5). Container stocktype had greater growth for all species at CR400, with container red oak and swamp white oak having double the growth of container stock at the Dugger site (Figure 2.5). An interaction of stocktype × herbicide was significant for all species second year diameter growth (Table 2.5). A similar trend with height growth was found with container generally having greater diameter growth except for black walnut and growth differences for all species and stocktypes, except bareroot red oak, became more pronounced with two years of herbicide use (Figure 2.6).

A significant interaction of site × shelter × herbicide on second year relative height growth was found for black walnut ($p = 0.0004$) but not for red oak ($p = 0.0564$) and swamp white oak ($p = 0.6721$, Table 2.4). At the Dugger site, shelter use and two years of herbicide significantly increased black walnut relative height growth compared to other combinations. However, at CR400, there were no differences between treatment combinations for red oak and swamp white oak, but black walnut without shelter and one year of herbicide had greater relative growth than with shelter and one year or without shelter and two years herbicide.

2.3.6 Total Height and Diameter

All species showed stocktype differences for total height and diameter (Tables 2.4 and 2.5) with bareroot stock taller (10-20 cm) and larger (1-3 mm) than container stock after two years (Figure 2.7). The trend of taller and larger bareroot than container seedlings was consistent throughout all interactions.

First year total height for black walnut had a significant interaction of site × stocktype × shelter ($p = 0.0180$, Table 2.4). Bareroot was significantly taller than container stocktype at both sites, however only at Dugger bareroot stocktype with shelter (63.3 ± 2.68 cm) was significantly less than without (80.5 ± 2.19 cm). In the second year, no species had a significant interaction of site × stocktype × herbicide for total height and each of the other three-way interactions was only significant for one species per interaction (Table 2.4). Black walnut and swamp white oak had a significant interaction of stocktype × shelter ($p = 0.0062$ and $p = 0.0019$, respectively) for second year total height. Both species followed the general trend of bareroot stocktype being taller than container, however shelter affected these species stocktypes differently, where shelter use resulted in reduced total height for bareroot black walnut while increasing total height for container swamp white oak.

Swamp white oak was the only species with a significant interaction of site × stocktype × shelter for total diameter each year. First year total diameter ($p = 0.0004$) was greater for bareroot stocktype regardless of shelter treatment at CR400 and Dugger; however, for second year total diameter ($p = 0.0345$) only bareroot without shelter had significantly greater total diameter than other treatment combinations at CR400. There were no differences between stocktypes regardless of shelter treatment at Dugger (Table 2.5).

2.3.7 Leaf water potential

Site was the only significant treatment found for leaf water potential across all species (Table 2.6). CR400 site had significantly higher water potential than Dugger (Figure 2.8). A significant interaction of site × herbicide was detected for swamp white oak ($p = 0.0062$). Dugger had significantly lower water potentials and herbicide was only significant at Dugger with one year of herbicide having the lowest water potential compared to two years of herbicide.

2.4 Discussion

2.4.1 Survival

Seedling survival through two years averaged 80% overall, which is greater than reported for afforestation (Jacobs et al. 2004) and other mine site plantings in Indiana (Chaney et al. 1995; Davis and Jacobs 2004). Our survival rates are similar for those reported at the same Dugger site after two years (Burney and Jacobs 2018). When either stocktype was protected by tree shelters, bareroot stock showed greater survival for black walnut and red oak as compared to container stock, which is in opposition to the hypothesis that container stock would have improved survival rates with shelters. Similarly, Sweeney et al. (2002) found no difference in survival between bareroot and container stocktypes protected by shelters in a riparian restoration area on the Eastern Shore of Maryland. Our results may be explained, in part, by the fact that there were no differences in root:shoot ratios between stocktypes, except for black walnut, where all stocktypes had a R/S ratio within the accepted range (1.0 – 3.0) which leads to improved survival chances (Grossnickle 2012). Bareroot stocktype typically experience loss of root mass, particularly fine roots, in the lifting and packing process which alters the R/S ratio and therefore impacts the ability of seedlings to hydraulically connect to the planting site (Struve and Joly 1992; Grossnickle 2005). R/S ratio is important for seedling survival as seedlings with balanced morphology likely have a large root system which avoids water stress after planting and therefore improve seedling survival particularly on harsher sites (Grossnickle 2005, 2012). Linked to this, initiation of new root growth after planting (i.e. root growth potential) has been shown to improve seedling water status, and by extension survival, as the seedling is able to begin exploring the soil profile for water and connect with the planting site (Grossnickle 2005, 2012). While not measured in this experiment, it could be expected that all stocktypes had high root growth potentials leading to successful coupling of seedlings to the site and resulting survival. Additionally, careful handling of both stocktypes during transport and planting may have also contributed to the high survival rates found in this trial.

Two of the three species selected for this trial, black walnut and red oak, had significant stocktype × shelter responses whereby shelters improved bareroot seedling survival over unsheltered seedlings. Thus, shelter use appeared to have a species specific stocktype responses for survival. Ponder (2003) found similar results for red oak planted in forest openings but contrasting results for black walnut (i.e., lower survival when sheltered) planted in an old agricultural field. In our study, swamp white oak was not affected by shelter use and had high survival at both sites, which is in agreement with Walter et al. (2013) where after five years, swamp white oak had 100% survival for bareroot and container stocktypes planted on an agricultural field. It should be noted that with bareroot seedlings, the average planting height was 60 cm which is double the shelter height (30 cm). The mechanism causing increased survival of bareroot over container stock with short shelters is not entirely clear in this study. However, seedlings in tree shelters allocate resources to increasing height over diameter and root growth (Mariotti et al. 2015). Bareroot seedlings that were taller than the shelters were likely less affected by the shelter environment, resulting in normal diameter and root growth patterns that may be the mechanism for increased survival.

Planting sites were reclaimed using different methods and there were several significant edaphic differences (Table 2.2), however site was not a significant factor for survival. Site was important in considering pre-dawn leaf water potentials with CR400 seedlings showing less water stress. As Grossnickle (2005, 2012) showed, seedling water status is directly connected to survival especially on harsher sites, yet there was not a relationship of increased survival of container stocktypes on the harsher Dugger site for any species. The maximum pre-dawn leaf water potential measured was around 0.8 MPa which is less than generally accepted range of 1.5

– 2.5 MPa for permanent wilting point (Pallardy and Kozlowski 2008), which may be why site was not a significant factor in seedling survival.

2.4.2 Growth

Stocktype was the greatest driver of seedling morphological differences after two years. As evidenced by the pre-planting sampling of seedling morphology, bareroot stocktype in all species were significantly taller and, except for swamp white oak, had larger diameters (Table 2.1). This trend follows what has been reported by Grossnickle and El-Kassaby (2016) where bareroot stock tend to be taller and have larger diameters compared to container stock of the same age; implying that taller seedlings will maintain height advantage over time (Grossnickle and MacDonald 2018). While the bareroot seedlings planted in this trial maintained a total height and diameter advantage over the two growing seasons, container seedlings reduced the difference during the two years (although still not matching bareroot seedlings). In contrast, Wilson et al. (2007) showed that for red oak planted in a clearcut, container stocktype matched or even out performed bareroot by the end of the first growing season. However, the positive trend in total height and diameter for container stock suggests that within subsequent seasons the difference may be negligible or even surpass bareroot totals.

Despite not fully supporting the hypothesis that herbicide treatments would improve growth performance of bareroot stocktype, all species showed improved relative diameter growth after two years of herbicide use for both stocktypes. Competing vegetation, particularly on post-SMCRA reclaimed sites, contributes to poor hardwood seedling survival and growth (Ashby 1997; Torbert and Burger 2000; Casselman et al. 2006; Skousen et al. 2009; Franklin et al. 2012) as heavy herbaceous cover can trap seedlings and create a dense overstory that smothers smaller seedlings (Torbert et al. 1995). Additionally, the herbaceous cover often out competes planted seedlings for soil moisture and nutrients (Grossnickle 2005). Seedlings in heavy herbaceous cover seek to increase height to attain a greater portion of available light for photosynthate production, and this is likely at the cost of allocating reserves to diameter and root growth. Control of vegetation in direct competition likely improves soil water, although this is not indicated in our water potential results, and nutrients available to planted seedlings thereby improving growth (Grossnickle 2005; Grossnickle and MacDonald 2018). Herbicide is a justified management tool for mine reclamation sites to effectively mitigate the deleterious effects of competing vegetation although herbicide use has been shown to increase browse incidence for planted seedlings (Ashby 1997; Dubois et al. 2000). Browse incidence in this experiment was not great (Appendix Table A.1), in part due to fencing and likely low populations of rabbits and rodents. Control of competing vegetation on sites with aggressive ground cover is required if restoration objectives are to be met.

My final hypothesis that shelter use would have a positive impact on container seedling growth was somewhat supported by our results for first year growth. Relative growth in height and diameter for container stock with shelters agreed with the literature whereby relative height growth was positively affected and relative diameter growth was negatively affected by shelters. Shelters have been shown to increase height growth and reduce diameter growth in *Quercus* species (Mechergui et al. 2013; Mariotti et al. 2015) due to alteration of above and belowground biomass allocation by protected seedlings. Seedlings in shelters allocate greater resources toward height growth which reduces photosynthate available for root growth. Additionally, species have specific seasonal growth patterns that can be enhanced or suppressed by shelters. For example, *Quercus* species have polycyclic growth and under ideal conditions can have multiple growth flushes in a single growing season as shown with *Q. robur* (Mariotti et al. 2015). Notably, shelters used in this experiment were only 30 cm while most shelters in the literature are 120 cm, which possibly is a confounding factor in this experiment as all of the bareroot stock planted were on average 60 cm; this could reduce any effect of shelters with this stocktype.

2.5 Conclusions

Establishment of hardwood tree seedlings on mine reclamation sites is difficult and management prescriptions are unique to individual sites. In general, container stocktype showed greater or equivalent field performance to bareroot stocktype, despite initial morphological differences, demonstrating efficacy for use on mine reclamation sites. Our results agree with the literature on stocktype interactions where height growth increases and diameter growth decreases with shelter use. In this study, herbicide use was an effective tool in promoting growth of hardwood tree seedlings on reclaimed mine sites. Swamp white oak was the most successful species planted in this experiment as far as survival and growth. While species interactions were not examined statistically, a general pattern that emerged among species was that swamp white oak showed generally good performance regardless of silvicultural treatment; black walnut and northern red oak, however, showed much stronger early regeneration responses to the silvicultural treatments tested in this study. Viewed altogether our results point back to utilizing the “Target Seedling Concept” (Landis 2011) in developing restoration prescriptions for reforestation of mine sites. Herbicide use in conjunction with container seedlings grown in larger sized containers would likely narrow the initial size differences to bareroot providing a high performing stocktype capable of successful establishment on harsh mine sites while still being economically feasible.

REFERENCES

Andersen C, Bussler B, Chaney W, Pope P, Byrnes W (1989) Concurrent establishment of groundcover and hardwood trees on reclaimed mineland and unmined reference sites. Forest Ecology and Management 28:81–99.

Andrews D, Barton C, Czapka S, Kolka R, Sweeney B (2010) Influence of tree shelters on seedling success in an afforested riparian zone. New Forests 39:157–167. doi: 10.1007/s11056-009-9161-8

Ashby W (1996) Red oak and black walnut growth increased with minesoil ripping. International Journal of Surface Mining, Reclamation and Environment 10:113–116. doi: 10.1080/09208119608964813

Ashby W (1999) Status of reforestation technology in southern Illinois. In: Vories KC, Throgmorton D (eds) Proceedings of Enhancement of Reforestation at Surface Coal Mines: Technical Interactive Forum. Co-sponsored by U.S. Department of Interior, Office of Surface Mining and Coal Research Center, Southern Illinois University, Fort Mitchell, KY, pp 109–124

Ashby W (1997) Soil ripping and herbicides enhance tree and shrub restoration on stripmines. Restoration Ecology 5:169–177. doi: 10.1046/j.1526-100X.1997.09720.x

Ashby W, Vogel W (1993) Tree Planting on Mined Lands in the Midwest: A Handbook. Coal Research Center, Southern Illinois University, Carbondale, IL

Barton C, Miller J, Sena K, Angel P, French M (2015) Evaluating the use of tree shelters for direct seeding of Castanea on a surface mine in Appalachia. Forests 6:3514–3527. doi: 10.3390/f6103514

Bateman JC, Chanasyk DS (2001) Effects of deep ripping and organic matter amendments on Ap horizons of soil reconstructed after coal strip-mining. Canadian Journal of Soil Science 81:113–120. doi: 10.4141/S00-105

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67:1–48. doi: 10.18637/jss.v067.i01

Burger J, Mitchem D, Scott D (2002) Field assessment of mine site quality for establishing hardwoods in the Appalachians. Proceedings of the American Society of Mining and Reclamation 226–240. doi: 10.21000/JASMR02010226

Burger J, Mitchem D, Zipper C, Williams R (2005) Herbaceous ground cover effects on native hardwoods planted on mined land. In: Proceedings of 2005 National Meeting of the America Society of Mining and Reclamation. ASMR, Breckenridge, CO, pp 136–146

Burney O, Jacobs D (2018) Species selection – A fundamental silvicultural tool to promote forest regeneration under high animal browsing pressure. Forest Ecology and Management 408:67–74. doi: 10.1016/j.foreco.2017.10.037

Bussler B, Byrnes W, Pope P, Chaney W (1984) Properties of minesoil reclaimed for forest land use. Soil Science Society of America Journal 48:178. doi: 10.2136/sssaj1984.03615995004800010033x

Casabon C, Pothier D (2007) Browsing of tree regeneration by white-tailed deer in large clearcuts on Anticosti Island, Quebec. Forest Ecology and Management 253:112–119. doi: 10.1016/j.foreco.2007.07.009

Casselman C, Fox T, Burger J, Jones A, Galbraith J (2006) Effects of silvicultural treatments on survival and growth of trees planted on reclaimed mine lands in the Appalachians. Forest Ecology and Management 223:403–414. doi: 10.1016/j.foreco.2005.12.020

Chaney W, Pope P, Byrnes W (1995) Tree survival and growth on land reclaimed in accord with Public Law 95-87. Journal of Environment Quality 24:630. doi: 10.2134/jeq1995.00472425002400040013x

Dallaire K, Skousen J, Schuler J (2015) Height of three hardwood species growing on mine sites reclaimed using the Forestry Reclamation Approach compared to natural conditions. Journal American Society of Mining and Reclamation 4:20–35. doi: 10.21000/JASMR15020020

Davis A, Jacobs D (2004) First-year survival of nothern red oak seedlings planted on former surface coal mines in Indiana. In: Barnhisel RI (ed) American Society of Mining and Reclamation. ASMR, Morgantown, WV, pp 480–502

Dey D, Jacobs D, McNabb K, Miller G, Baldwin V, Foster G (2008) Artificial regeneration of major oak (Quercus) species in the eastern United States--A review of the literature. Forest Science 54:77–106.

Dubois M, Chappelka A, Robbins E, Somers G, Baker K (2000) Tree shelters and weed control: Effects on protection, survival and growth of cherrybark oak seedlings planted on a cutover site. New Forests 20:105–118. doi: 10.1023/A:1006704016209

Energy Information Administration (2016) Annual Coal Report 2015. Washington, D.C.

Fields-Johnson C, Burger J, Evans D, Zipper C (2014) Ripping improves tree survival and growth on unused reclaimed mined lands. Environmental Management 53:1059–1065. doi: 10.1007/s00267-014-0261-7

Fralish JS (2003) The Central Hardwood Forest: its boundaries and physiographic provinces. In: Van Sambeek J, Dawson J, Ponder F, Loewenstein E, Fralish J (eds) 13th Central Hardwood Forest conference. USDA Forest Service, North Central Research Station, Urbana, IL, pp 1–20

Franklin J, Zipper C, Burger J, Skousen J, Jacobs D (2012) Influence of herbaceous ground cover on forest restoration of eastern US coal surface mines. New Forests 43:905–924. doi: 10.1007/s11056-012-9342-8

Groninger J, Fillmore S, Rathfon R (2006) Stand characteristics and productivity potential of Indiana surface mines reclaimed under SMCRA. Northern Journal of Applied Forestry 23:94–99.

Grossnickle S (2005) Importance of root growth in overcoming planting stress. New Forests 30:273–294. doi: 10.1007/s11056-004-8303-2

Grossnickle S (2012) Why seedlings survive: Influence of plant attributes. New Forests 43:711–738. doi: 10.1007/s11056-012-9336-6

Grossnickle S, El-Kassaby Y (2016) Bareroot versus container stocktypes: A performance comparison. New Forests 47:1–51. doi: 10.1007/s11056-015-9476-6

Grossnickle SC, MacDonald JE (2018) Why seedlings grow: influence of plant attributes. New Forests 49:

Hackworth ZJ, Springer MT (2018) First-year vitality of reforestation plantings in response to herbivore exclusion on reclaimed Appalachian surface-mined land. Forests 9:1–14. doi: 10.3390/f9040222

Hankin S, Karst J, Landhäusser S (2015) Influence of tree species and salvaged soils on the recovery of ectomycorrhizal fungi in upland boreal forest restoration after surface mining. Botany 93:267–277. doi: 10.1139/cjb-2014-0132

Jacobs D (2011) Reforestation of a salvage-logged high-elevation clearcut : Engelmann spruce seedling response to tree shelters after 11 growing seasons. Western Journal of Applied Forestry 26:53–56.

Jacobs D, Ross-Davis A, Davis A (2004) Establishment success of conservation tree plantations in relation to silvicultural practices in Indiana, USA. New Forests 28:23–36. doi: 10.1023/B:NEFO.0000031329.70631.d0

Jacobs D, Salifu K, Davis A (2009) Drought susceptibility and recovery of transplanted *Quercus rubra* seedlings in relation to root system morphology. Annals of Forest Science 66:504–504. doi: 10.1051/forest/2009029

Johnson P, Novinger S, Mares W (1984) Root, shoot, and leaf area growth potentials of northern red oak planting stock. Forest Science 30:1017–1026.

Johnston J, Pope P, Schwab A, Kladivko E, Jacobs D, Swihart R (2012) “Hardwood Reforestation on Post-Mined Land under Varying Soil Replacement Strategies in the Eastern Interior Region.” Purdue University

Kjelgren R, Montague D, Rupp L (1997) Establishment in treeshelters II: Effect of shelter color on gas exchange and hardiness. Horticultural Science 32:1284–1287.

Kjelgren R, Rupp L (1997) Establishment in treeshelters I: Shelters reduce growth, water use, and hardiness, but not drought avoidance. Horticultural Science 32:1281–1283.

Kuznetsova A, Brockhoff P, Christensen R (2017) lmerTest package: Tests in linear mixed effects models. Journal of Statistical Software. doi: 10.18637/jss.v082.i13

Landis T (2011) The target plant concept - a history and brief overview. In: Riley LE, Haase DL, Pinto JR (eds) National Proceedings: Forest and Conservation Nursery Associations - 2010. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, pp 61–66

Lenth R V. (2016) Least-squares means: The R package lsmeans. Journal of Statistical Software. doi: 10.18637/jss.v069.i01

Long R, Brose P, Horsley S (2012) Responses of northern red oak seedlings to lime and deer exclosure fencing in Pennsylvania. Canadian Journal of Forest Research 42:698–709. doi: 10.1139/x2012-025

Mariotti B, Maltoni A, Jacobs D, Tani A (2015) Tree shelters affect shoot and root system growth and structure in *Quercus robur* during regeneration establishment. European Journal of Forest Research 134:641–652. doi: 10.1007/s10342-015-0878-y

McKay H (1997) A review of the effect of stresses between lifting and planting on nursery stock quality and performance. New Forests 13:369–399. doi: 10.1023/A:1006563130976

McKenna J, Krauss O, Beheler B (2011) A highly efficient machine planting system for forestry research plantations — The Wright-MSU Method. Tree Planters' Notes 54:32–37.

Mechergui T, Pardos M, Boussaidi N, Hasnaoui B, Jacobs D (2013) Development of cork oak (*Quercus suber* L.) seedlings in response to tree shelters and mulching in northwestern Tunisia. Journal of Forestry Research 24:193–204. doi: 10.1007/s11676-013-0345-x

National Research Council (2007) Coal: Research and Development to Support National Energy Policy. National Academies Press, Washington, D.C.

Oliet J, Jacobs D (2007) Microclimatic conditions and plant morpho-physiological development within a tree shelter environment during establishment of *Quercus ilex* seedlings. Agricultural and Forest Meteorology 144:58–72. doi: 10.1016/j.agrformet.2007.01.012

Oliet J, Planelles R, Artero F, Domingo-Santos J (2016) Establishing *Acacia salicina* under dry Mediterranean conditions: The effects of nursery fertilization and tree shelters on a mid-term experiment with saline irrigation. Ciencia e Investigacion Agraria 43:7–7. doi: 10.4067/S0718-16202016000100007

Olyphant G, Harper D (1995) Effects of direct revegetation on the hydrology, erosion and sediment yield of an abandoned deposit of coal-mine refuse. Geomorphology 11:261–272.

Pallardy S, Kozlowski T (2008) Absorption of Water and. In: Physiology of Woody Plants, 3rd edn. Elsevier, Boston, pp 287–323

Pallardy S, Pereira J, Parker W (1991) Measuring the state of water in tree systems. In: Lassioe J, Hinckley T (eds) Techniques and Approaches in Forest Tree Ecophysiology. CRC Press, Boca Raton, FL, pp 28–76

Ponder F (2003) Ten-year results of tree shelters on survival and growth of planted hardwoods. Northern Journal of Applied Forestry 20:104–108.

Potter M (1988) Tree shelters improve survival and increase growth rates. Forestry 86:39–41.

Probert T (1992) Forest productivity of reclaimed mined land: A landowner’s perspective. In: American Society of Mining and Reclamation. Duluth, MN, pp 756–762

Rodrigue J, Burger J (2004) Forest soil productivity of mined land in the Midwestern and Eastern coalfield regions. Soil Science Society of America Journal 68:833. doi: 10.2136/sssaj2004.0833

Rodrigue J, Burger J, Oderwald R (2002) Forest productivity and commercial value of pre-law reclaimed mined land in the eastern United States. Northern Journal of Applied Forestry 19:106–114.

Ruess R, Hendrick R, Bryant J (1998) Regulation of fine root dynamics by mammalian browsers in early successional Alaskan taiga forests. Ecology 79:2706–2720. doi: 10.1890/0012-9658(1998)079[2706:ROFRDB]2.0.CO;2

Salifu K, Jacobs D, Birge Z (2009) Nursery nitrogen loading improves field performance of bareroot oak seedlings planted on abandoned mine lands. Restoration Ecology 17:339–349. doi: 10.1111/j.1526-100X.2008.00373.x

Scullion J, Malinovszky K (1995) Soil factors affecting tree growth on former opencast coal land. Land Degradation & Development 6:239–249. doi: 10.1002/ldr.3400060405

Sharew H, Hairston-Strang A (2005) A comparison of seedling growth and light transmission among tree shelters. Northern Journal of Applied Forestry 22:102–110.

Skousen J, Dallaire K, Scagline-Mellor S, Monteleone A, Wilson-Kokes L, Joyce J, Thomas C, Keene T, DeLong C, Cook T, Jacobs D (2018) Plantation performance of chestnut hybrids and progenitors on reclaimed Appalachian surface mines. New Forests. doi: 10.1007/s11056-018-9643-7

Skousen J, Gorman J, Pena-Yewtukhiw E, King J, Stewart J, Emerson P, Delong C (2009) Hardwood tree survival in heavy ground cover on reclaimed land in West Virginia: mowing and ripping effects. Journal of Environment Quality 38:1400–9. doi: 10.2134/jeq2008.0297

Sloan J, Jacobs D (2013) Fertilization at planting influences seedling growth and vegetative competition on a post-mining boreal reclamation site. New Forests 44:687–701. doi: 10.1007/s11056-013-9378-4

Sloan J, Uscola M, Jacobs D (2016) Nitrogen recovery in planted seedlings, competing vegetation, and soil in response to fertilization on a boreal mine reclamation site. Forest Ecology and Management 360:60–68. doi: 10.1016/j.foreco.2015.10.024

Stange E, Shea K (1998) Effects of deer browsing, fabric mats, and tree shelters on *Quercus rubra* seedlings. Restoration Ecology 6:29–34. doi: 10.1046/j.1526-100x.1998.00614.x

Struve D, Joly R (1992) Transplanted red oak seedlings mediate transplant shock by reducing leaf surface area and altering carbon allocation. Canadian Journal of Forest Research 22:1441–1448.

Sweeney B, Czapka S, Yerkes T (2002) Riparian forest restoration: Increasing success by reducing plant competition and herbivory. Restoration Ecology 10:392–400. doi: 10.1046/j.1526-100X.2002.02036.x

Taylor T, Loewenstein E, Chappelka A (2006) Effect of animal browse protection and fertilizer application on the establishment of planted Nuttall oak seedlings. New Forests 32:133–143. doi: 10.1007/s11056-005-4167-3

Torbert J, Burger J (2000) Forest land reclamation. In: Barnhisel R, Darmody R, Daniels W (eds) Reclamation of drastically disturbed lands. Agronomy Monograph 41, 2nd edn. ASA, CSSA, SSSA, Madison, WI, pp 371–398

Torbert J, Burger J, Daniels W (1990) Pine growth variation associated with overburden rock type on a reclaimed surface mine in Virginia. Journal of Environmental Quality 19:88–92. doi: 10.2134/jeq1990.00472425001900010011x

Torbert J, Burger J, Probert T (1995) Evaluation of techniques to improve white pine establishment on an Appalachian minesoil. Journal of Environmental Quality 24:869–873. doi: 10.2134/jeq1995.00472425002400050012x

Tripler C, Canham C, Inouye R, Schnurr J (2002) Soil nitrogen availability, plant luxury consumption, and herbivory by white-tailed deer. Oecologia 133:517–524. doi: 10.1007/s00442-002-1046-x

Tuley G (1985) The growth of young oak in shelters. Forestry 58:181–195.

US Congress (1977) Surface Mining Control and Reclamation Act of 1977. United States

Valkonen S (2008) Survival and growth of planted and seeded oak (*Quercus robur* L.) seedlings with and without shelters on field afforestation sites in Finland. Forest Ecology and Management 255:1085–1094. doi: 10.1016/j.foreco.2007.10.038

Walter W, Godsey L, Garrett H, Dwyer J, Van Sambeek J, Ellersieck M (2013) Survival and 14-year growth of black, white, and swamp white oaks established as bareroot and RPM (R)-containerized planting stock. Northern Journal of Applied Forestry 30:43–46. doi: 10.5849/njaf.11-047

Wilson E, Vitols K, Park A (2007) Root characteristics and growth potential of container and bare-root seedlings of red oak (*Quercus rubra* L.) in Ontario, Canada. New Forests 34:163–176. doi: 10.1007/s11056-007-9046-7

Woolery P, Jacobs D (2014) Planting stock type and seasonality of simulated browsing affect regeneration establishment of *Quercus rubra*. Canadian Journal of Forest Research 44:732–739. doi: 10.1139/cjfr-2013-0492

Woolery P, Jacobs D (2011) Photosynthetic assimilation and carbohydrate allocation of *Quercus rubra* seedlings in response to simulated herbivory. Annals of Forest Science 68:617–624. doi: 10.1007/s13595-011-0064-4

Zaczek J, Steiner K, Bowersox T (1997) Northern red oak planting stock: 6-year results. New Forests 13:177–191. doi: 10.1023/A:1006578007777

Zipper C, Burger J, McGrath J, Rodrigue J, Holtzman G (2011) Forest restoration potentials of coal-mined lands in the eastern United States. Journal of Environmental Quality 40:1567–1577. doi: 10.2134/jeq2011.0040

Table 2.1 Pre-planting seedling morphological measurements (means ± SE) for each hardwood species and two stocktypes (n = 12). Means in columns not followed by the same letter are significantly different ($p < 0.05$). Note: species are analyzed separately.

Species	Stocktype	Height (cm)	Diameter (mm)	Root dry mass (g)	Shoot dry mass (g)	R:S Ratio
Black walnut	Bareroot	70.8 ± 4.8[a]	13.7 ± 1.8[a]	19.8 ± 3.0[a]	14.3 ± 1.8[a]	1.4 ± 0.14[b]
	Container	27.7 ± 2.1[b]	8.9 ± 0.3[b]	3.6 ± 0.9[b]	1.5 ± 0.2[b]	2.2 ± 0.28[a]
Red oak	Bareroot	63.6 ± 3.8[a]	10.6 ± 0.6[a]	17.1 ± 2.0[a]	10.8 ± 1.4[a]	1.7 ± 0.15[a]
	Container	28.7 ± 0.7[b]	7.5 ± 0.3[b]	2.9 ± 0.4[b]	1.9 ± 0.2[b]	1.5 ± 0.13[a]
Swamp white oak	Bareroot	50.8 ± 4.8[a]	7.9 ± 0.4[a]	7.5 ± 1.4[a]	5.0 ± 1.0[a]	1.6 ± 0.13[a]
	Container	27.5 ± 1.2[b]	8.4 ± 0.4[a]	3.9 ± 0.5[b]	2.6 ± 0.3[b]	1.5 ± 0.06[a]

Table 2.2 Soil properties of CR400 and Dugger (means ± SE, n = 6 bulked samples/site) respectively. CR400 was abandoned mine land reclaimed in 2013 and Dugger was post-SMCRA reclaimed in 1995. Means in rows not followed by the same letter are significantly different ($p < 0.05$). meq, milliequivalents; ppm, parts per million.

	CR400	Dugger
Organic matter (%)	3.20 ± 0.01[a]	2.8 ± 0.01[b]
Soil pH	6.01 ± 0.24[a]	6.16 ± 0.14[a]
Cation exchange capacity (meq/100g)	20.83 ± 1.28[a]	11.21 ± 0.45[b]
Bulk density (g/cm^3)	1.30 ± 0.01[a]	1.26 ± 0.01[a]
Phosphorous (ppm)	7.00 ± 0.97[a]	3.08 ± 0.50[b]
Potassium (ppm)	102.83 ± 4.19[a]	107.08 ± 5.84[a]
Magnesium (ppm)	280.42 ± 28.47[a]	308.33 ± 9.07[a]
Calcium (ppm)	2779.17 ± 149.17[a]	1250 ± 62.46[b]
Carbon:nitrogen	26.22 ± 0.87[a]	14.67 ± 1.25[b]
Texture	Clay Loam	Silty Clay Loam

Table 2.3 Analysis of variance test results for first and second year survival by site (df =1), stocktype (df = 1), shelter (df = 1), herbicide (df = 1) and all possible two-way interactions (BW, black walnut; RO, red oak; SWO, swamp white oak). Significant interactions are in bold ($p < 0.05$).

Parameter	Site (S)	Stocktype (St)	Shelter (Sh)	Herbicide (H)	S x St	S x Sh	S x H	St x Sh	St x H	Sh x H
Survival 1 yr										
BW	0.5256	0.3321	**0.0022**	**0.0002**	0.8471	0.4630	**0.0006**	**0.0031**	0.1431	0.4960
RO	0.8354	0.7599	0.3260	0.7786	**0.0468**	0.3198	0.4554	0.0823	0.2312	0.6626
SWO	0.8983	0.6359	0.5159	0.5194	0.5614	0.1316	0.7189	0.2116	0.1066	0.7184
Survival 2 yr										
BW	0.9706	0.8850	**0.0040**	**< 0.0001**	0.6530	0.4104	**< 0.0001**	**0.0011**	0.0511	0.7996
RO	0.2116	**0.0302**	0.0560	0.8160	**0.0009**	0.5184	0.6775	**0.0179**	0.9481	0.8737
SWO	0.7456	0.5591	0.6589	0.1991	0.2862	**0.0440**	0.4064	0.8843	**0.0090**	0.5454

Table 2.4 Analysis of variance test results for first and second year height parameters by site (df =1), stocktype (df = 1), shelter (df = 1), herbicide (df = 1) and all possible interactions, up to three-way, separated by species (BW, black walnut; RO, red oak; SWO, swamp white oak). Significant effects are in bold ($p < 0.05$). Rel. Ht1, height growth of first year relative to planting height; Rel. Ht2, height growth of second year relative to first year height; Tot. Ht1, total height of first year; Tot. Ht2, total height of second year.

Parameters	Site (S)	Stocktype (St)	Shelter (Sh)	Herbicide (H)	S x St	S x Sh	S x H	St x Sh	St x H	Sh x H	S x St x Sh	S x St x H	S x Sh x H	St x Sh x H
Rel. Ht1														
BW	**0.0335**	**< 0.0001**	**0.0231**	0.0719	0.2563	0.6825	**0.0070**	**< 0.0001**	0.8603	**0.0378**	0.3112	0.0587	0.1910	**0.02719**
RO	**0.0359**	**< 0.0001**	0.0845	0.1786	**< 0.0001**	0.1562	0.6811	**0.0034**	0.4010	0.0676	0.0567	0.5585	0.1194	0.6727
SWO	**< 0.0001**	**< 0.0001**	**0.0048**	0.6276	0.1244	0.3184	0.0906	0.5231	0.7267	0.1459	0.0691	0.3769	**0.0263**	0.4795
Rel. Ht2														
BW	**< 0.0001**	**< 0.0001**	**0.0008**	**0.0002**	**0.0106**	**0.0182**	**0.0140**	**0.0001**	**0.0227**	**< 0.0001**	0.2555	0.2555	0.7952	**0.0004**
RO	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.0913	**< 0.0001**	**0.0004**	**0.0217**	**0.0034**	0.3748	0.7900	0.0612	0.6504	0.4369	0.0564
SWO	**< 0.0001**	**< 0.0001**	**0.0023**	**0.0092**	**< 0.0001**	0.1419	0.1801	**0.0201**	0.2024	**0.0062**	0.9399	0.2936	0.0995	0.6721
Tot. Ht1														
BW	0.3076	**< 0.0001**	**0.0071**	**0.0099**	0.1572	**0.0015**	**0.0005**	**< 0.0001**	0.1861	0.6768	**0.0180**	**0.0027**	0.0528	0.3303
RO	**0.0463**	**< 0.0001**	0.1662	**0.0100**	0.1693	0.8287	0.9095	0.2466	**0.0075**	0.6055	0.9748	0.8277	**0.0005**	0.3879
SWO	0.0746	**< 0.0001**	**0.0055**	0.1288	**0.0045**	0.1020	0.0570	0.1783	0.7396	0.6194	0.3994	0.3735	0.5114	0.0806
Tot. Ht2														
BW	0.5459	**< 0.0001**	0.3529	**< 0.0001**	0.7245	0.3067	**0.0004**	**0.0062**	0.6706	**< 0.0001**	0.7732	0.0707	**0.0417**	0.1684
RO	**0.0025**	**< 0.0001**	**< 0.0001**	**0.0005**	**0.0126**	**0.0017**	0.7832	0.7742	**0.0489**	**0.0015**	0.1496	0.3222	0.5813	**0.0023**
SWO	**0.0041**	**< 0.0001**	**< 0.0001**	0.1213	0.0964	**0.0226**	0.4820	**0.0019**	0.9164	0.0991	**0.0322**	0.4099	0.9148	0.3399

Table 2.5 Analysis of variance test results for first and second year diameter parameters by site (df =1), stocktype (df = 1), shelter (df = 1), herbicide (df = 1) and all possible interactions, up to three-way, separated by species (BW, black walnut; RO, red oak; SWO, swamp white oak). Significant interactions are in bold ($p < 0.05$). Rel. D1, diameter growth of first year relative to planting diameter; Rel. D2, diameter growth of second year relative to first year diameter; Tot. D1, total diameter of first year; Tot. D2, total diameter of second year.

Parameters	Site (S)	Stocktype (St)	Shelter (Sh)	Herbicide (H)	S x St	S x Sh	S x H	St x Sh	St x H	Sh x H	S x St x Sh	S x St x H	S x Sh x H	St x Sh x H
Rel. D1														
BW	0.2462	**< 0.0001**	0.4220	0.7858	**0.0041**	0.9860	**0.0016**	**0.0003**	0.9069	0.1681	0.7829	**0.0001**	0.6455	0.6407
RO	0.2096	0.0650	**0.0027**	0.4322	0.9815	0.8058	0.4790	0.3102	0.3154	**0.0133**	0.5894	0.8635	0.6012	0.0537
SWO	0.4578	**0.0006**	0.6106	**0.0204**	0.3785	0.4657	**0.0133**	**0.0155**	**0.0374**	**0.0066**	0.2416	0.8157	**0.0122**	**0.0148**
Rel. D2														
BW	0.5377	**< 0.0001**	**0.0372**	**< 0.0001**	0.2942	0.5884	0.0566	**0.0252**	**< 0.0001**	0.0677	0.0582	0.0926	0.6337	0.8060
RO	**< 0.0001**	**< 0.0001**	0.3374	**0.0063**	0.3110	0.1836	**< 0.0001**	0.6842	**0.0023**	0.8449	**0.0082**	0.1513	0.7684	0.0720
SWO	**< 0.0001**	**< 0.0001**	0.1081	**< 0.0001**	**0.0236**	**0.0030**	**< 0.0001**	**0.0305**	**< 0.0001**	**< 0.0001**	0.9727	**0.0057**	**< 0.0001**	0.6874
Tot. D1														
BW	0.3608	**< 0.0001**	**0.0396**	0.3571	0.0883	0.1431	0.1878	0.9925	0.0695	0.0504	0.2982	0.4771	0.8399	0.6245
RO	**0.0439**	**< 0.0001**	0.3852	0.9190	**0.0044**	**0.0001**	0.2218	**0.0438**	0.6467	**0.0292**	**0.0111**	0.8785	0.5906	**0.0065**
SWO	**0.0059**	**< 0.0001**	**0.0301**	0.7269	0.4250	**0.0121**	0.3124	**0.0056**	**0.0459**	0.9007	**0.0004**	0.2699	0.2397	0.4003
Tot. D2														
BW	0.3781	**< 0.0001**	**0.0035**	**< 0.0001**	0.5961	0.8860	**0.0027**	0.1890	**< 0.0001**	0.3661	0.1748	0.9196	0.2481	**0.0223**
RO	**0.0128**	**< 0.0001**	0.9770	**0.0075**	0.0591	**0.0004**	**0.0024**	0.1367	0.3825	0.6964	0.4437	0.4057	0.7513	0.2239
SWO	**0.0013**	**0.0004**	**0.0230**	**< 0.0001**	0.8843	**0.0002**	**< 0.0001**	**0.0062**	**0.0282**	**0.0154**	**0.0345**	0.3005	**0.0001**	0.4983

Table 2.6 Analysis of variance test results for pre-dawn leaf water potential by site (df =1), stocktype (df = 1), herbicide (df = 1) and all possible interactions separated by species (BW, black walnut; RO, red oak; SWO, swamp white oak). Significant interactions are in bold ($p < 0.05$).

Parameter	Site (S)	Stocktype (St)	Herbicide (H)	S x St	S x H	St x H	S x St x H
Leaf Ψ_{pd}							
BW	**0.0219**	0.3395	0.4401	0.6853	0.7181	0.0728	0.0804
RO	**0.0016**	0.9283	0.7008	0.1618	0.3144	0.8428	0.7475
SWO	**< 0.0001**	0.7925	0.7613	0.2643	**0.0062**	1.0000	0.4476

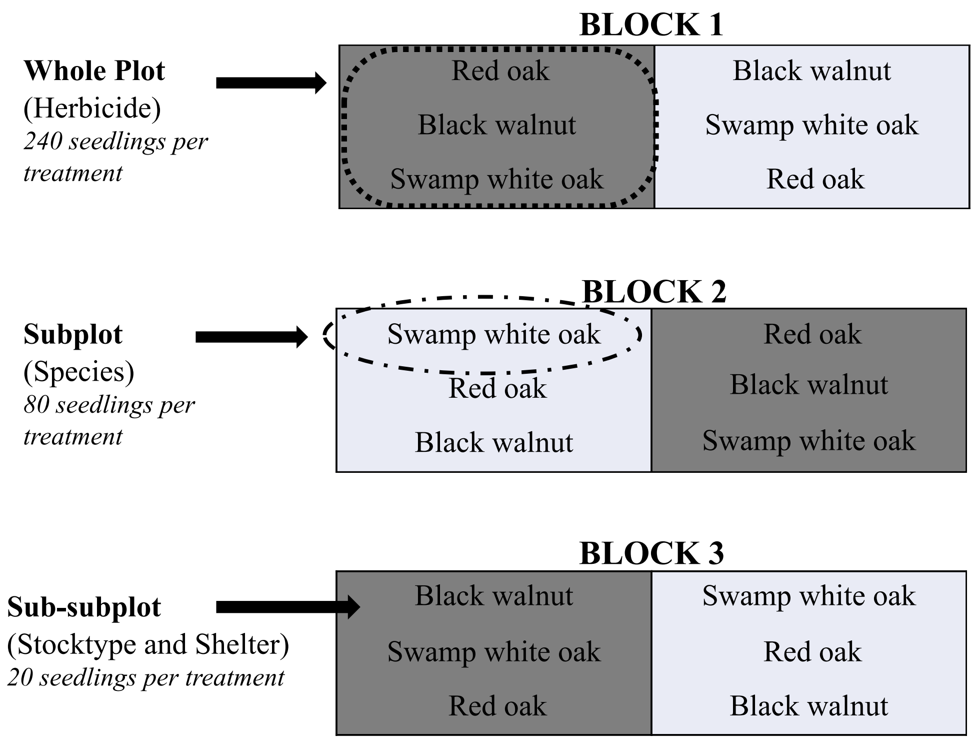

Figure 2.1 Example of the experimental design at one planting site using a factorial structure of 3 species × 2 herbicide treatments (1 year or 2 years of herbicide) × 2 nursery stocktype treatments (bareroot or container) × 2 browse control treatments (tree shelter or none). Light gray color of plots indicates one year of herbicide and dark gray indicates two years of herbicide.

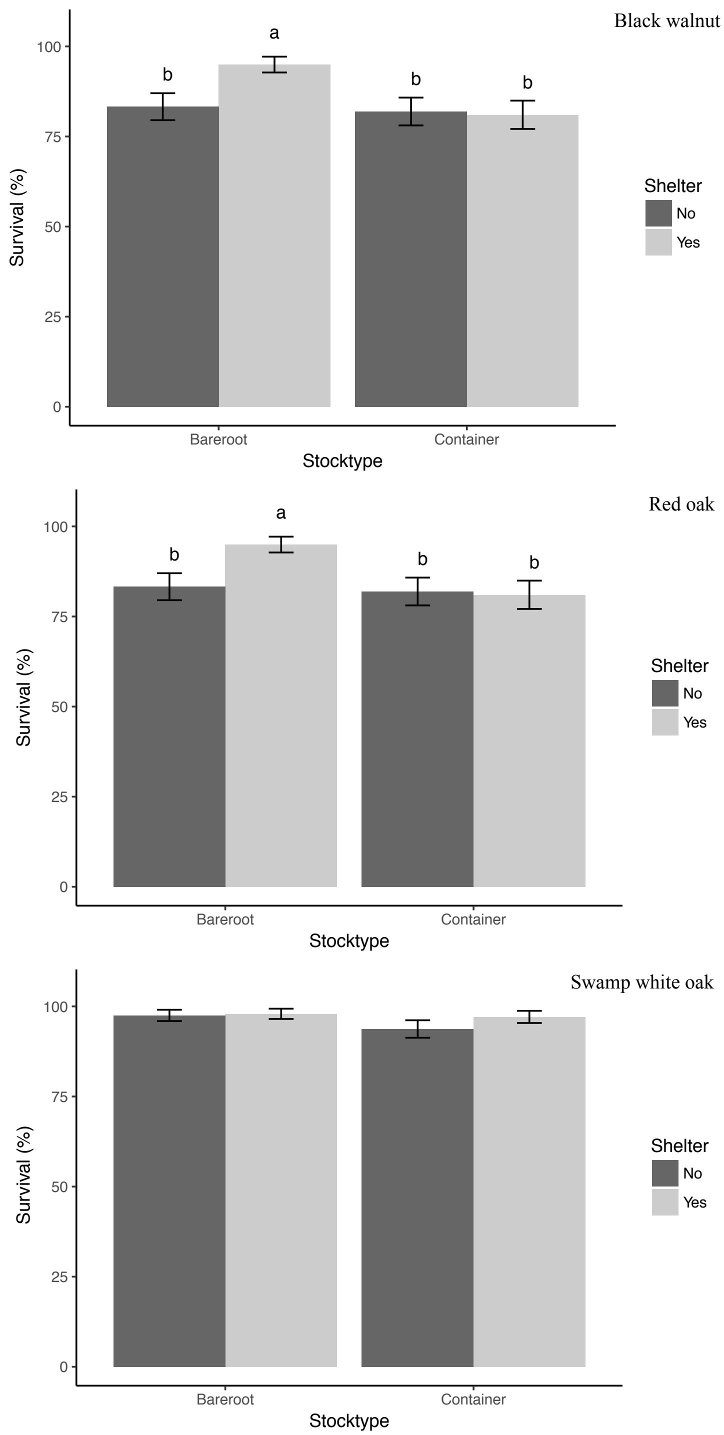

Figure 2.2 Percent survival after two years of black walnut, red oak, and swamp white oak for stocktype × shelter interaction. Columns represent means and bars represent ± 1 SD. Columns with different letters are statistically different according at $\alpha = 0.05$. Columns without letters indicates interaction not statistically significant.

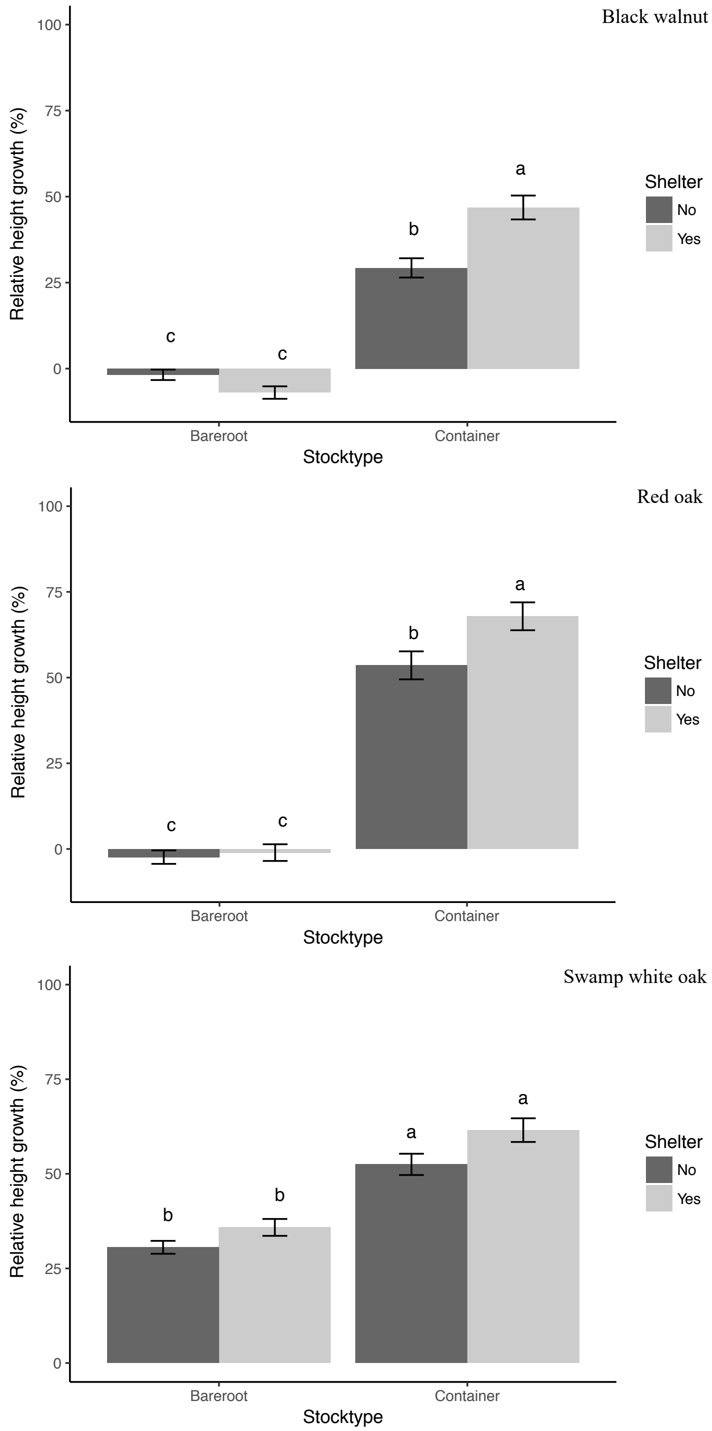

Figure 2.3 Mean relative height growth of 1-year-old black walnut, red oak, and swamp white oak for stocktype × shelter interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

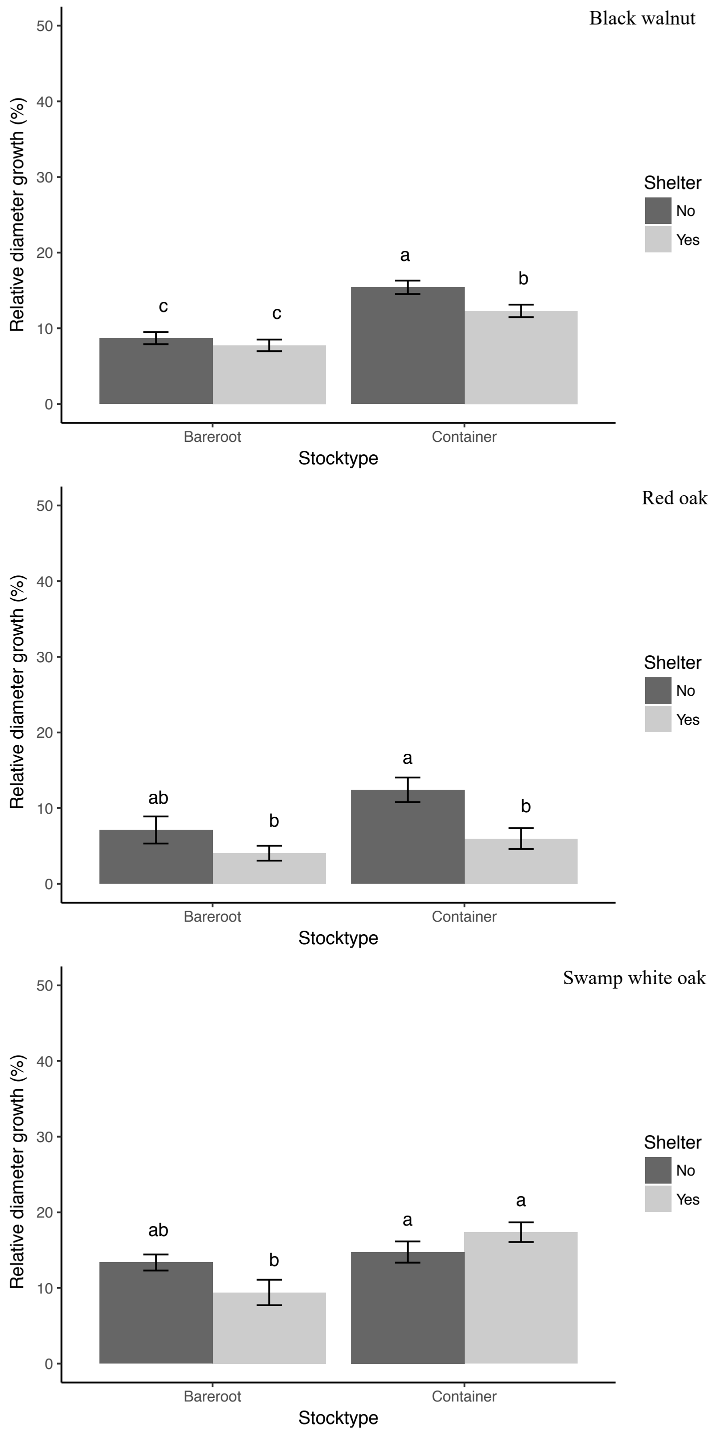

Figure 2.4 Mean relative ground line diameter (GLD) growth of 1-year-old black walnut, red oak, and swamp white oak for stocktype × shelter interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

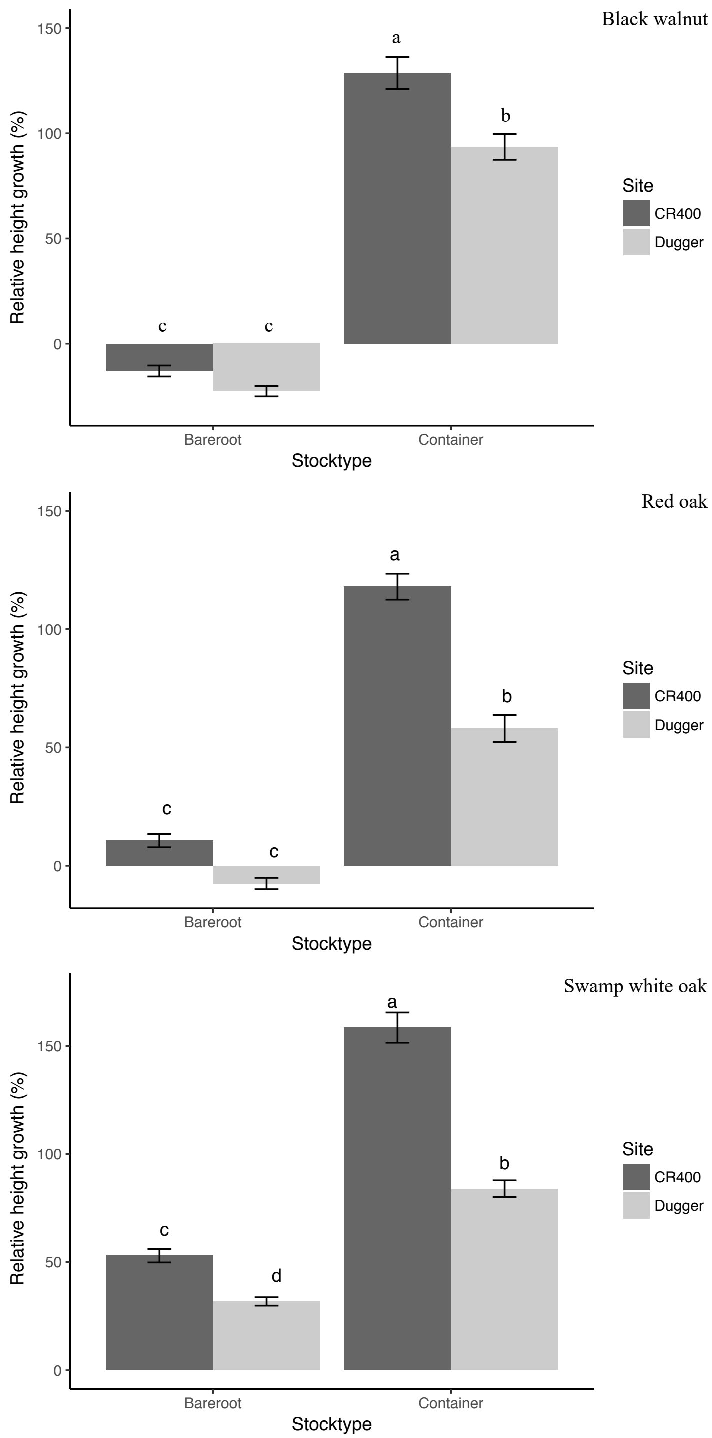

Figure 2.5 Mean relative height growth of 2-year-old black walnut, red oak, and swamp white oak for site × stocktype interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

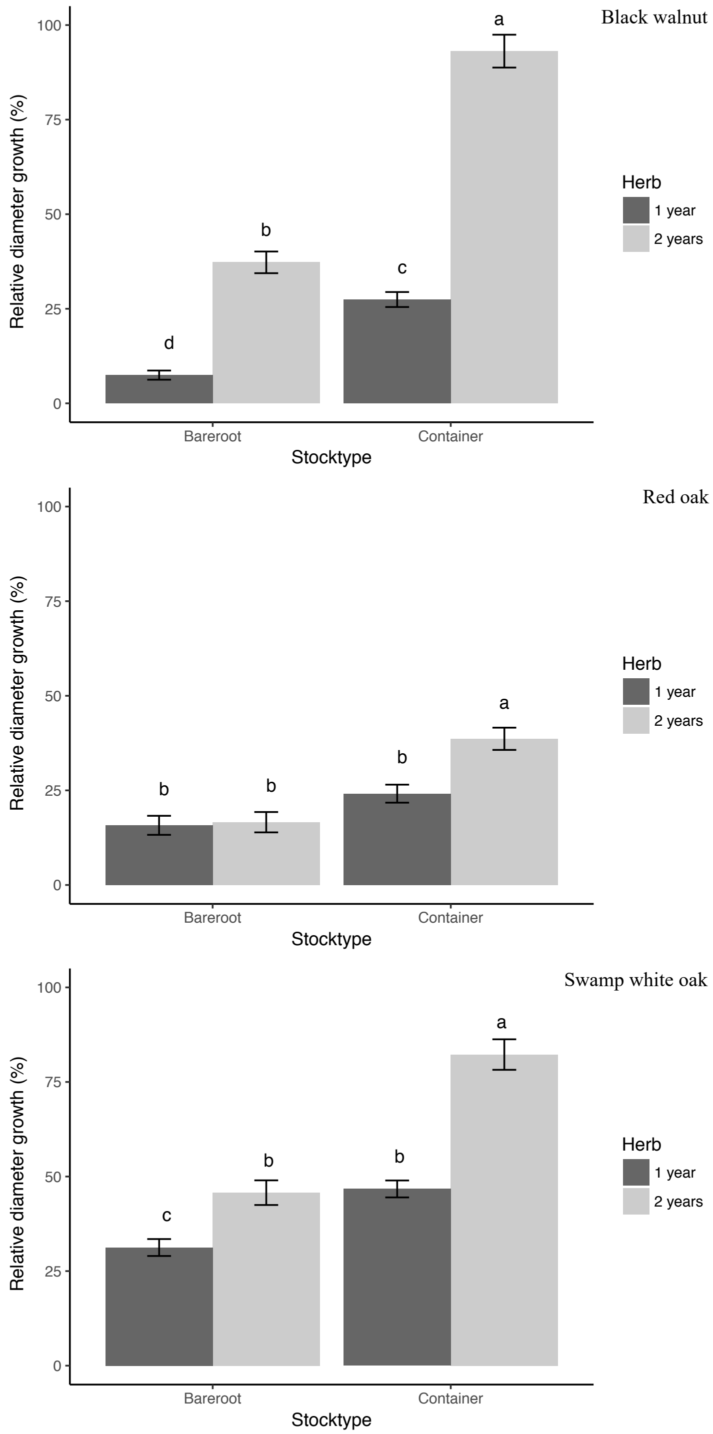

Figure 2.6 Mean relative diameter growth of 2-year-old black walnut, red oak, and swamp white oak for stocktype × herbicide interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

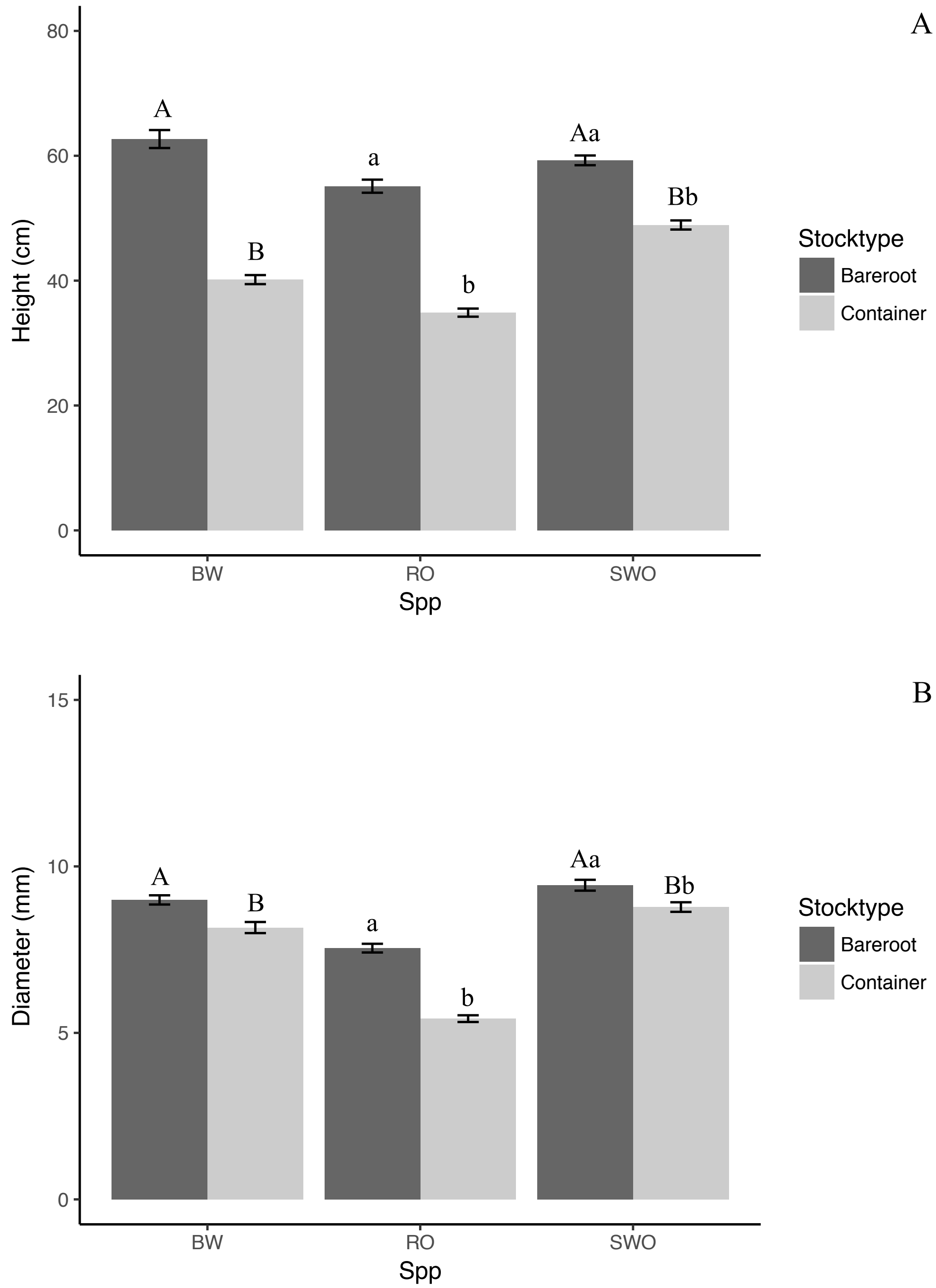

Figure 2.7 Second year total height (A) and diameter (B) for black walnut (BW), red oak (RO), and swamp white oak (SWO) by stocktype. Columns are means and error bars are (± 1 SE). Species were analyzed separately. Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

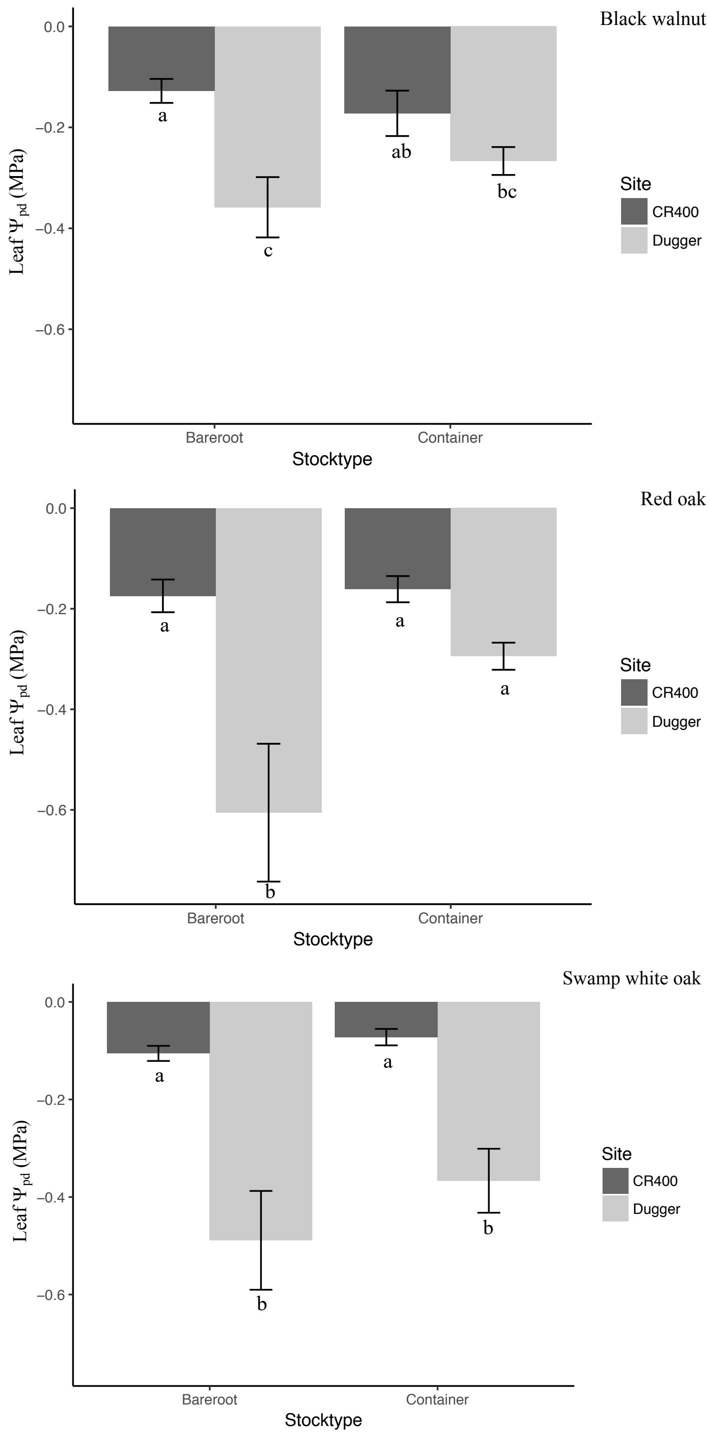

Figure 2.8 Mean leaf pre-dawn water potential (Ψpd) for each site and stocktype. Columns are means and error bars are (± 1 SE).

APPENDIX

Table A.1 Browse incidence (actual counts 2nd year) for species, stocktype, and shelter treatments by deer, rabbit, or vole at CR400 and Dugger respectively (BW, black walnut; RO, red oak; SWO, swamp white oak).

Site	Species	Stocktype	Shelter	Deer	Rabbit	Vole
CR400	BW	Bareroot	No	0	0	0
			Yes	0	0	4
		Container	No	0	0	0
			Yes	0	0	0
	RO	Bareroot	No	7	0	1
			Yes	7	0	0
		Container	No	5	0	0
			Yes	6	0	1
	SWO	Bareroot	No	1	0	1
			Yes	0	0	0
			No	2	0	0
		Container	Yes	1	0	0
Dugger	BW	Bareroot	No	0	0	1
			Yes	0	0	0
		Container	No	0	1	1
			Yes	0	0	0
	RO	Bareroot	No	9	6	2
			Yes	1	0	0
		Container	No	0	7	0
			Yes	1	0	0
	SWO	Bareroot	No	4	2	0
			Yes	0	1	0
		Container	No	3	2	1
			Yes	3	0	0
			Total	50	19	12

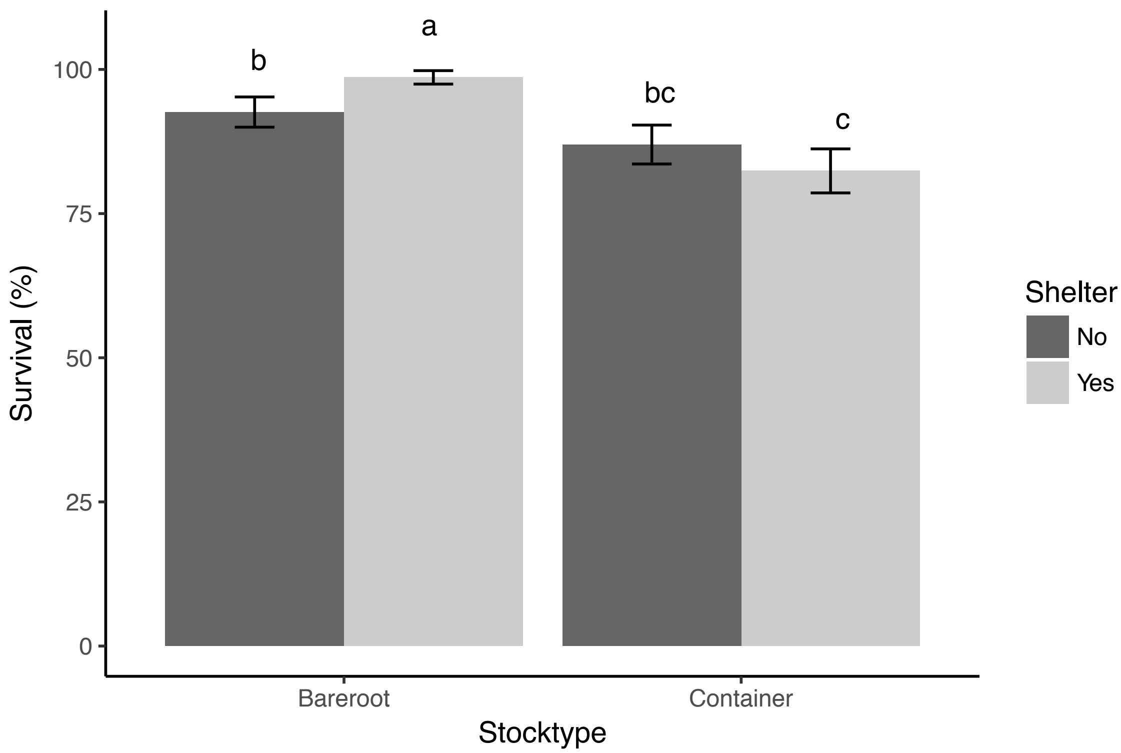

Figure A.1 Percent survival after one year for black walnut for stocktype × shelter interaction. Columns represent means and bars represent ± 1 SD. Colums with different letters are statistically different at $\alpha = 0.05$.

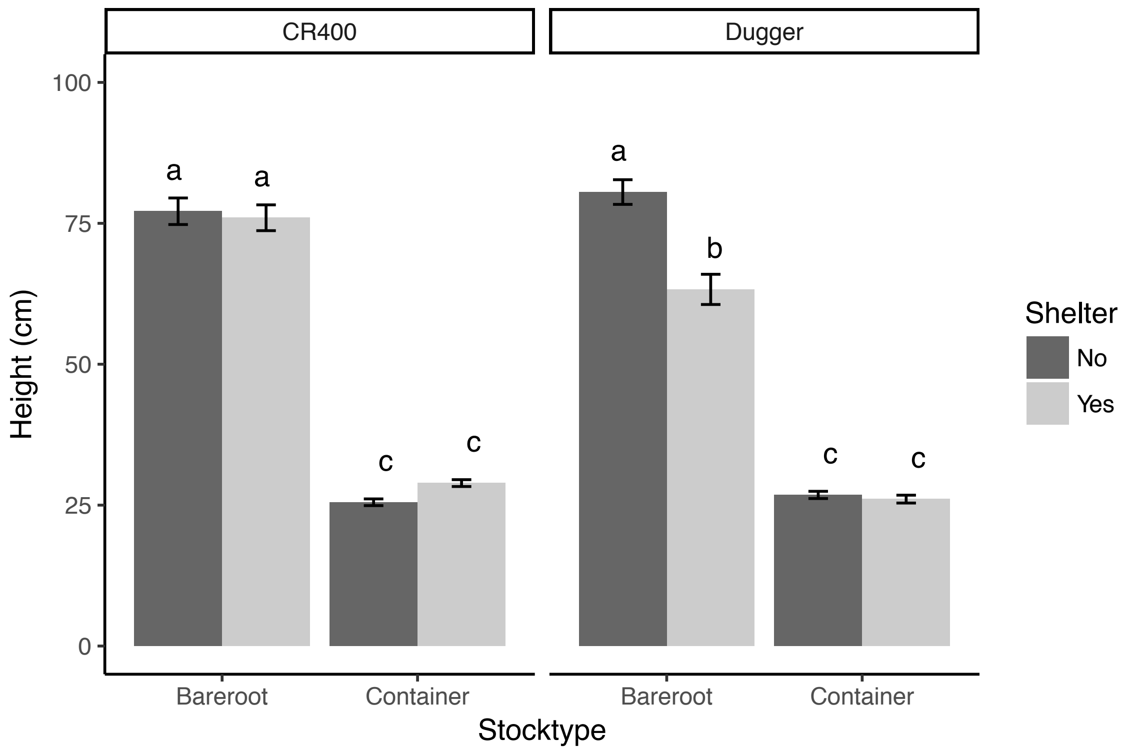

Figure A.2 First year total height of black walnut for site × stocktype × shelter interaction. Columns are means and error bars are (± 1SE). Columns that have the same letters within letter groupings are not significantly different at α = 0.05.

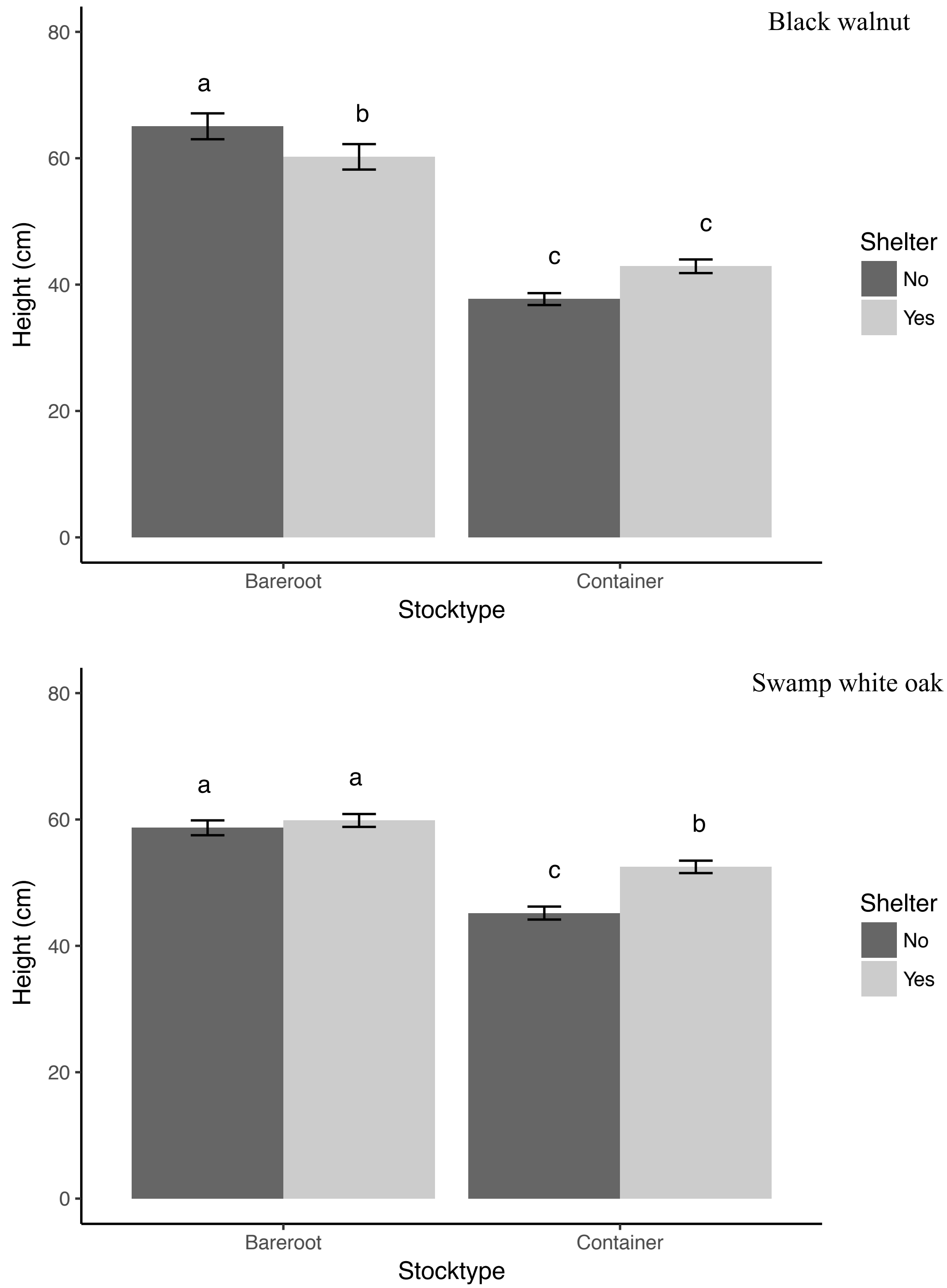

Figure A.3 Second year total height for black walnut and swamp white oak for the stocktype × shelter interaction. Columns are means and bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

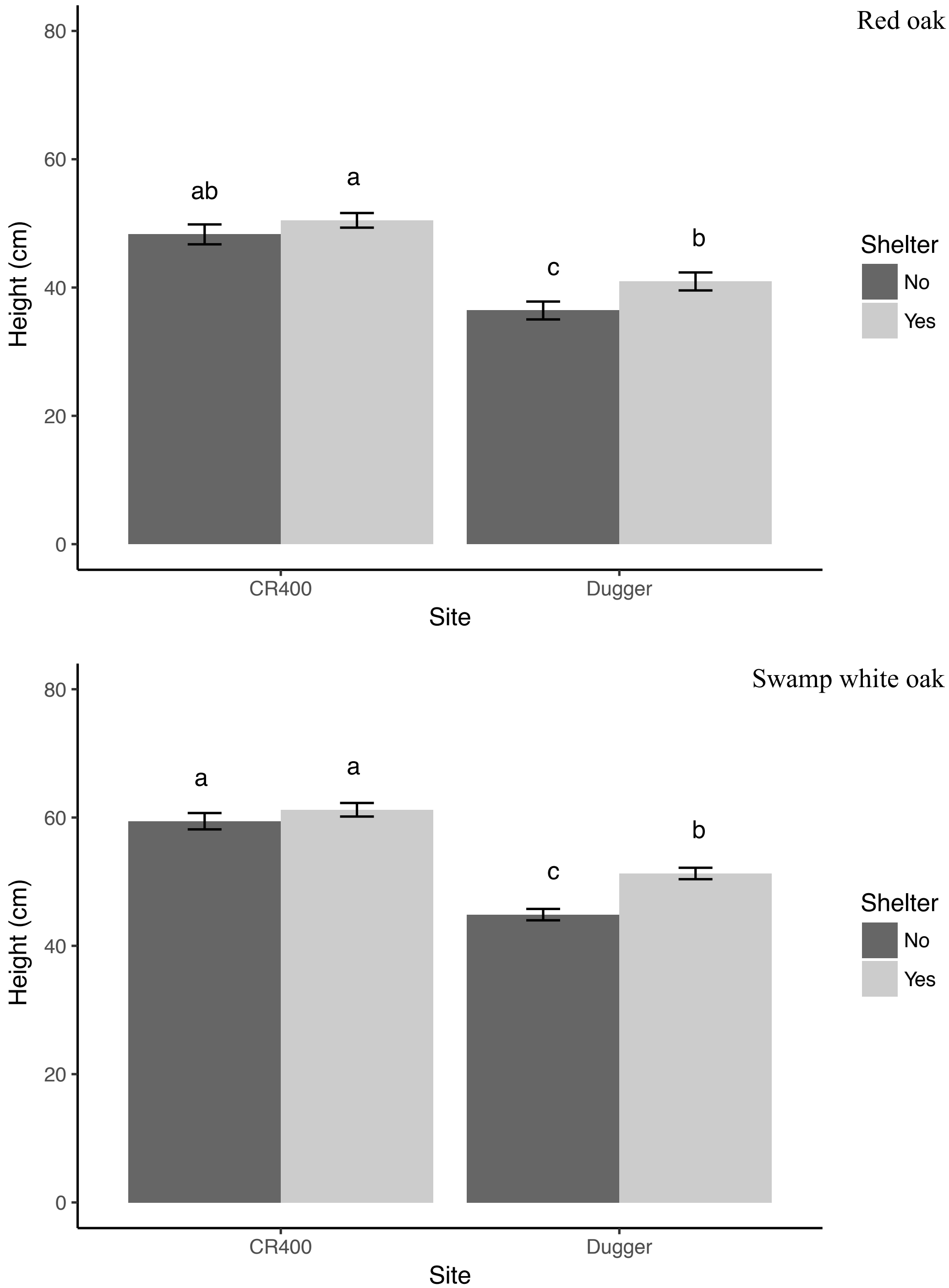

Figure A.4 Second year total height for red oak and swamp white oak for the site × shelter interaction. Columns are means and bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at α = 0.05.

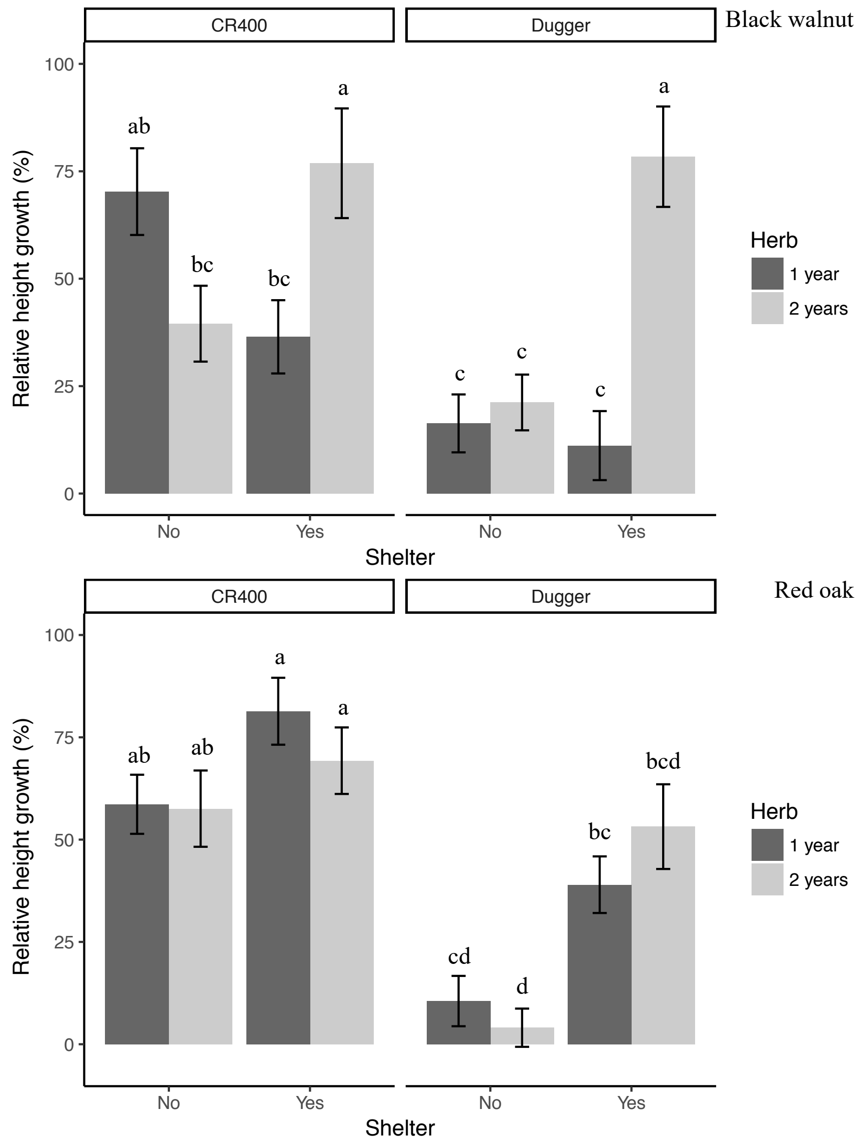

Figure A.5 Mean relative height growth of 2-year-old black walnut and red oak for site × shelter × herbicide. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at α = 0.05.

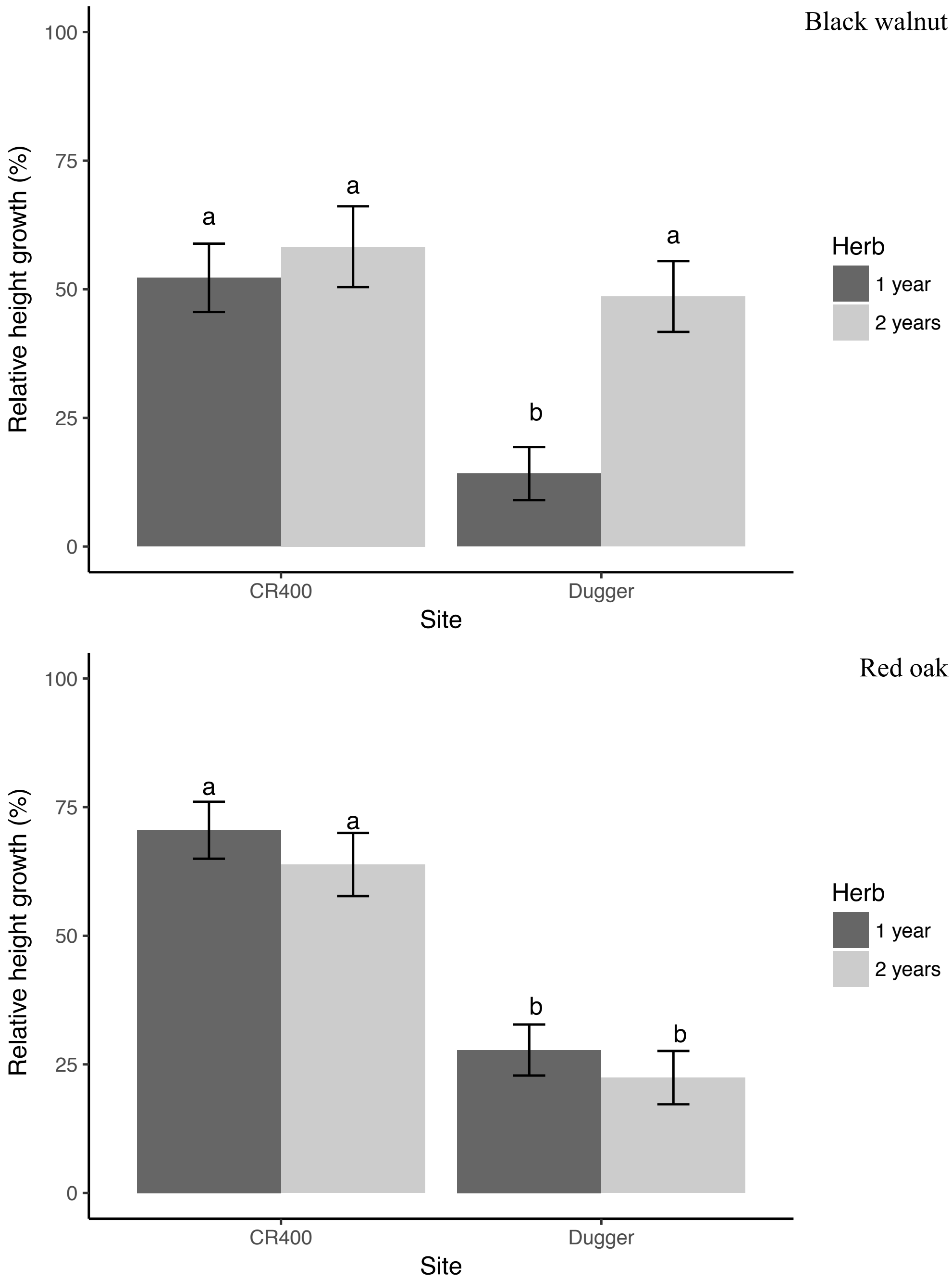

Figure A.6 Mean relative height growth of 2-year-old black walnut and red oak for site × herbicide interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

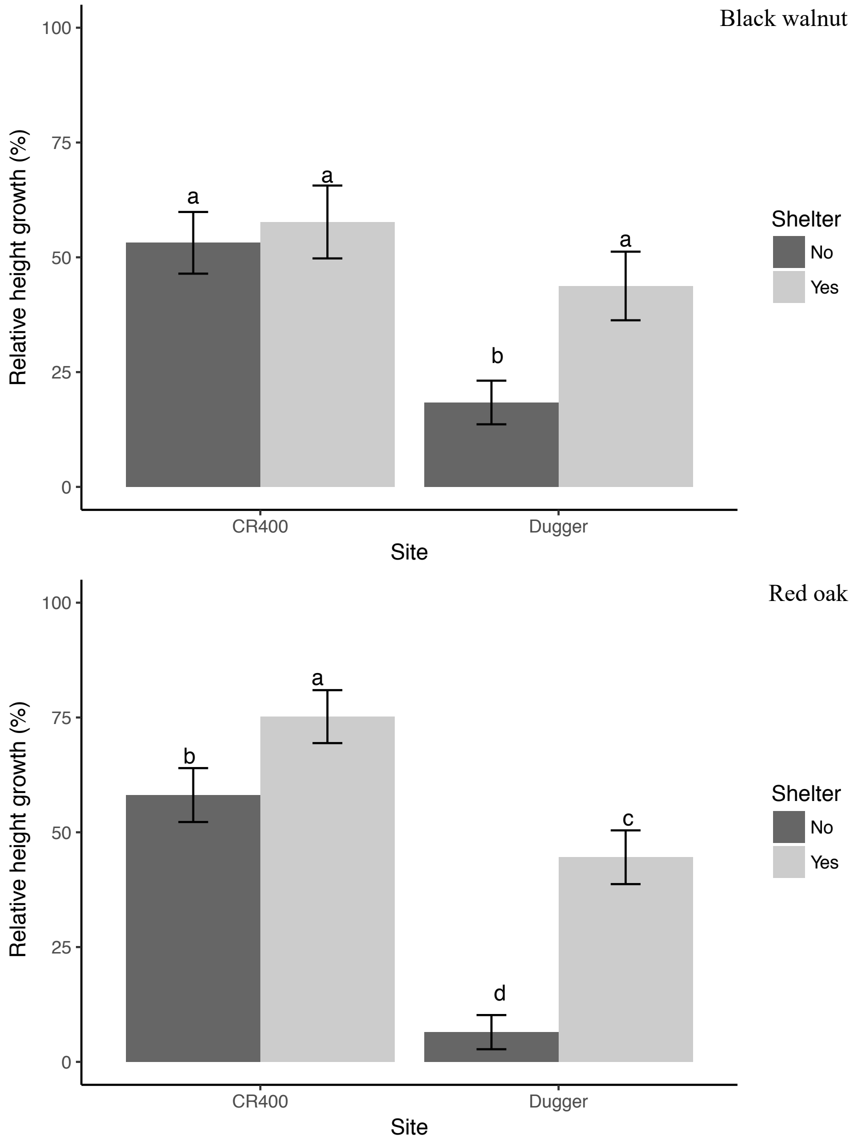

Figure A.7 Mean relative height growth of 2-year-old black walnut, red oak for site × shelter interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

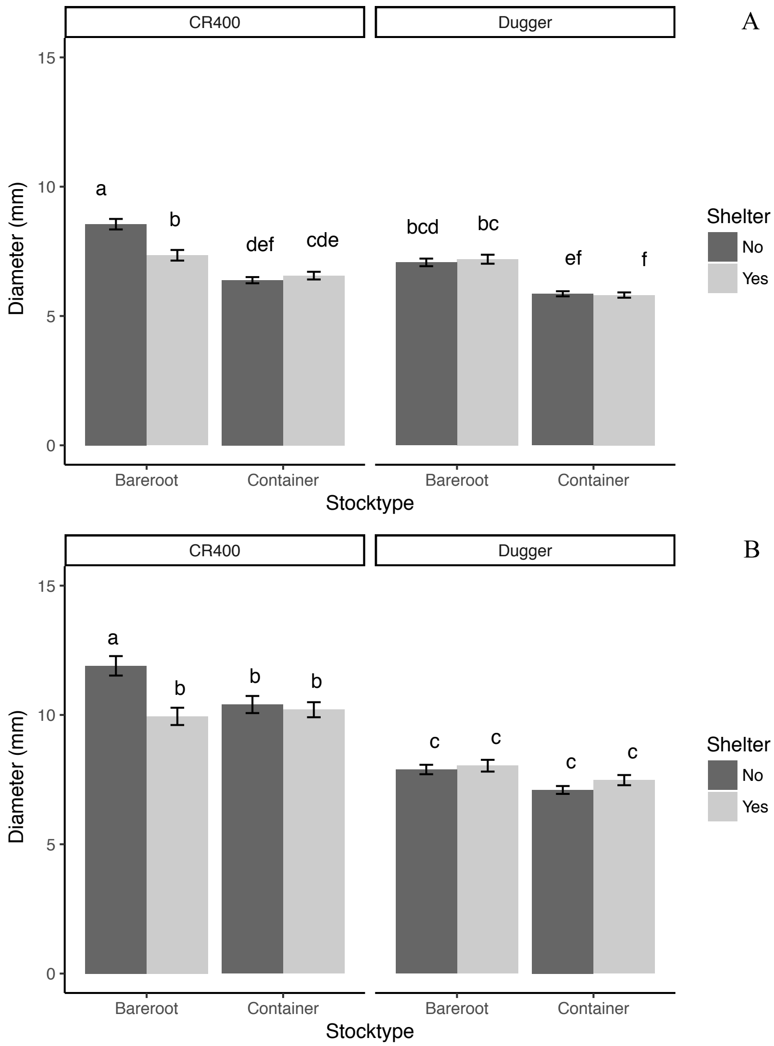

Figure A.8 One year (A) and two year (B) total diameter of swamp white oak for site × stocktype × shelter interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

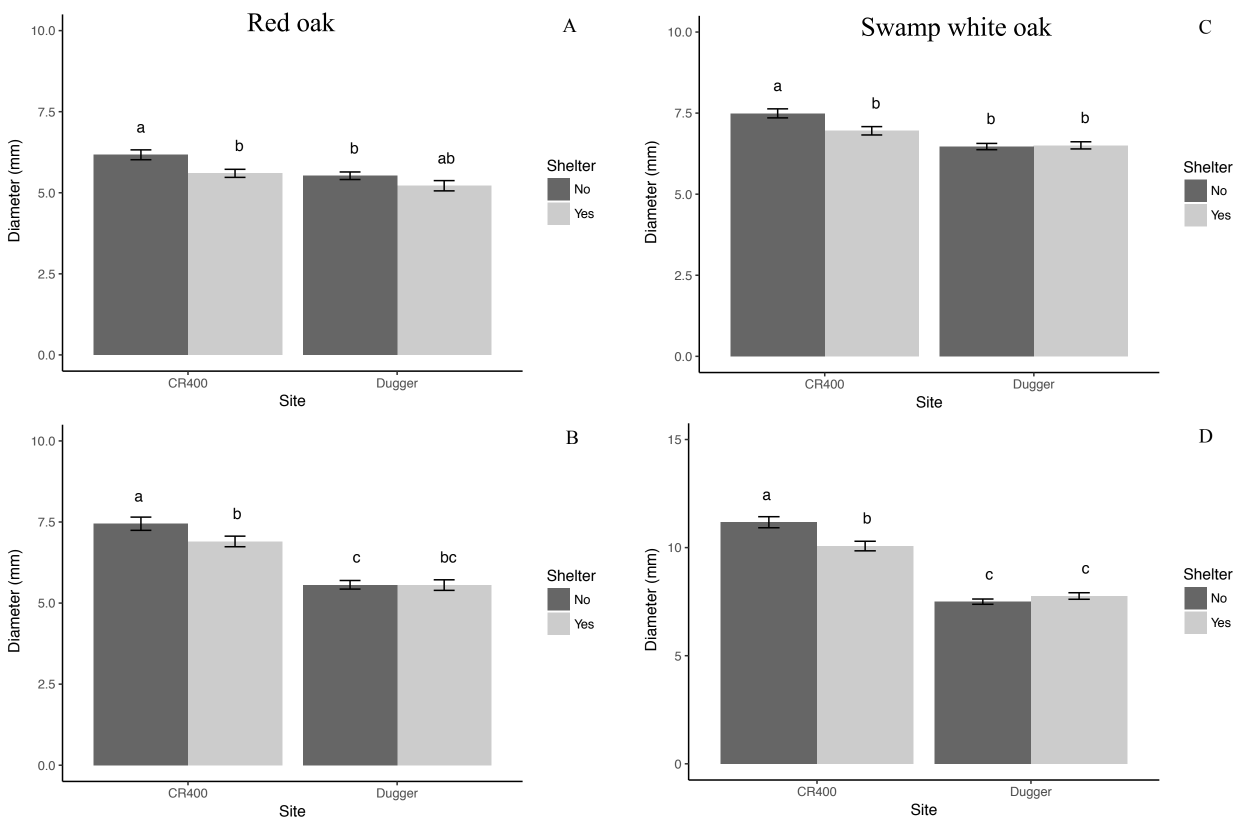

Figure A.9 One year (A) and two year (B) total diameter of red oak and one year (C) and two year (D) total diameter of swamp white oak for site × shelter interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

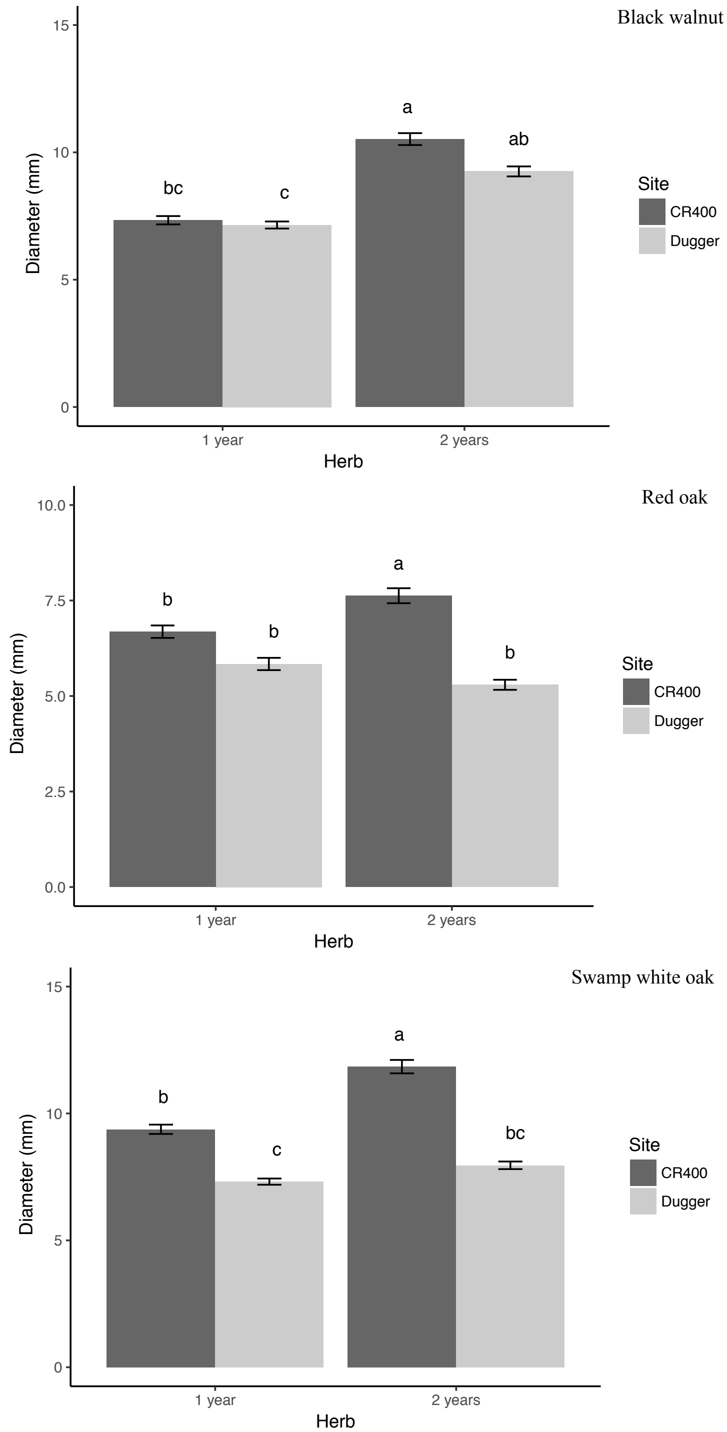

Figure A.10 Second year total diameter of black walnut, red oak, and swamp white oak for site × herbicide interaction. Columns are means and error bars are (± 1 SE). Columns that have the same letters within letter groupings are not significantly different at $\alpha = 0.05$.

Figure A.11 Typical soil core from soil sampling.

Figure A.12 Examples of container (0 + 1) stocktype grown at Woody Warehouse in Lizton, IN. Lower photo courtesy of Dr. Douglass Jacobs.

Figure A.13 Typical bareroot (1 + 0) stocktype grown at the Indiana Department of Forestry and Natural Resources State Nursery near Vallonia, IN. Photo courtesy of Dr. Douglass Jacobs.

Figure A.14 Example of tree shelter treatment used for this study. Shelter were 30-cm tall by 10-cm wide, vented polyethylene tubes anchored with either bamboo or white oak stakes.

Figure A.15 CR400 site showing two years of herbicide treatment.

Figure A.16 Dugger site showing two years of herbicide treatment.