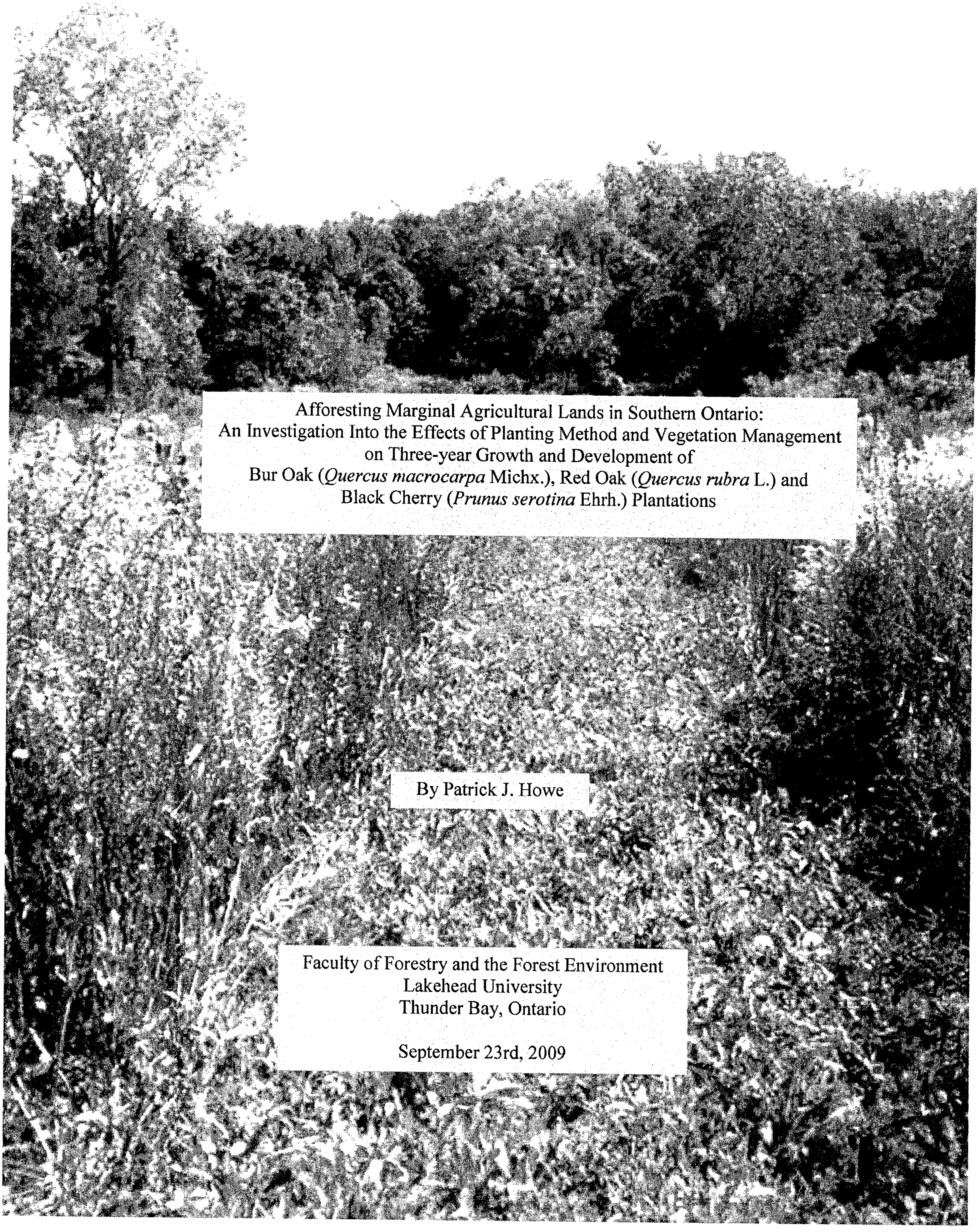

Afforesting Marginal Agricultural Lands in Southern Ontario: An Investigation Into the Effects of Planting Method and Vegetation Management on Three-year Growth and Development of Bur Oak (*Quercus macrocarpa* Michx.), Red Oak (*Quercus rubra* L.) and Black Cherry (*Prunus serotina* Ehrh.) Plantations

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September 23rd, 2009

AFFORESTING MARGINAL AGRICULTURAL LANDS IN SOUTHERN ONTARIO: AN INVESTIGATION INTO THE EFFECTS OF PLANTING METHOD AND VEGETATION MANAGEMENT ON THREE-YEAR GROWTH AND DEVELOPMENT OF BUR OAK (*Quercus macrocarpa* Michx.), RED OAK (*Quercus rubra* L.) AND BLACK CHERRY (*Prunus serotina* Ehrh.) PLANTATIONS

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A Graduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Forestry

Faculty of Forestry and the Forest Environment

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A CAUTION TO THE READER

This M.Sc.F. thesis has been through a formal process of review and comment by three faculty members and an external reviewer. It is made available for loan by the Faculty of Forestry and the Forest Environment for the purpose of advancing the practice of professional and scientific forestry.

The reader should be aware that opinions and conclusions expressed in this document are those of the student and do not necessarily reflect the opinions of either the thesis supervisor, the faculty or Lakehead University.

ABSTRACT

Howe, P. J. 2009. Afforesting marginal agricultural lands in southern Ontario; an investigation into the effects of planting method and vegetation management on three-year growth and development of bur oak (*Quercus macrocarpa* Michx.), red oak (*Quercus rubra* L.) and black cherry (*Prunus serotina* Ehrh.) plantations. 74pp.

Keywords: allometric relationships, afforestation, biomass accumulation, direct seeding, *Prunus serotina, Quercus macrocarpa, Quercus rubra*, planted seedlings, vegetation management.

Landowners in southern Ontario have become increasingly interested in afforesting marginal agricultural land. There are few appropriate, up-to-date research studies on afforestation practices to support current practice. Research into the growth and development of forests planted on marginal land has lagged substantially behind forest research in natural settings. Thus an opportunity exists to provide practical and relevant information to landowners to be used in the plantation management planning process.

This study was established as a side-by-side comparison of two planting methods (direct seeding and transplants) and three vegetation management treatments (no treatment, one-time plastic mulch application and annual herbicide application) and their influence on the growth and development of bur oak (*Quercus macrocarpa* Michx.), red oak (*Quercus rubra* L.) and black cherry (*Prunus serotina* Ehrh.) plantations. Three-year growth and development data were then coupled with an estimation of root, shoot and total biomass accumulation over three years to develop a summary tool. This summary tool can scale up single tree metrics to a plantation scale and provide landowners with a practical forecast to judge the accomplishment of management objectives such as carbon sequestration.

The results of this study show that direct seeding cannot produce comparable biomass relative to transplants, but can establish a comparable density of stems after three years. Three-year results also show that herbicide use is the most effect method of vegetation management. Trees grown under plastic mulch had comparable mean results to trees treated with herbicide but their results were much more inconsistent. Red oak was the most versatile species. It grew well as a transplant and from seed. Black cherry's germination was poor and unreliable but as a transplant it thrived.

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INTRODUCTION

In the late 1800s farmers were planting trees to control soil erosion; today the practice of afforestation offers a much more diverse set of benefits (Anonymous 2001, Sweeney *et al.* 2007). As a result of urban sprawl, economic pressures other factors, smaller farming operations across Ontario have been abandoned. There are over 300,000 ha of marginal agricultural land in the province left abandoned that could be growing trees (Bird and Boysen 2007). The modern landowner recognizes this potential and is seeking ways to manage farm woodlots to produce a new set of services. Non-timber forest products, game habitat, recreational opportunities, aesthetic value, carbon sequestration and the conservation of biodiversity are all values that can be derived from afforested plantations, which can supersede the value of traditional products of lumber and maple syrup (Vesterdal *et al.* 2002, Anonymous 2003, Gardiner *et al.* 2004, Ross-Davis *et al.* 2005, Nui and Duiker 2006, Xianzeng and Duiker 2006).

Despite new interest in farm forests the same resource challenges of the past face current landowners. Finding the money, labour, equipment and the trees required to complete an afforestation project is difficult and usually represents a commitment that a farmer is unwilling to make on his own. Fortunately, there are a variety of programs offered by the provincial government and local conservation authorities that provide financial and technical assistance to private landowners in Ontario. These programs, such as the 50 million Tree Program offered by Trees Ontario, provide landowners with financial aid for planting operations. They give landowners the technical, operational and financial assistance required to afforest or reforest small (<10 ha) parcels of land (Anonymous 2001, White and Kurz 2005).

In 2004, the Ontario Ministry of Natural Resources, the Upper Thames Conservation Authority, the Ontario Ministry of Agriculture and Food and the Lakehead University Faculty of Forestry and the Forest Environment identified that landowners needed a set of resources to help them make informed decisions about their afforestation projects. In particular, research was needed into the growth and development of afforested plantations using non-traditional management techniques. This group recognized a wealth of research into plantation development in natural settings and a gap in related knowledge on marginal agricultural lands. As a result, a project was developed to begin to bridge that gap by complementing the work done in the natural environment and improving forest management in agricultural settings.

Being an informed manager is the first step in developing a successful afforestation project. This thesis begins with a literature review that outlines common decisions that must be made before the first tree is planted. In providing detailed information on site and species selection, planting methods, vegetation management and threats to afforested plantations the literature review can be a valuable extension resource for landowners. The literature review also compiles research on biomass accumulation in young plantations. The summary details how to quantify biomass in plantations and how landowners may manage their plantations with biomass accumulation as a management goal.

An experimental study builds on the literature review and addresses two key knowledge gaps. The first is the need for more research into alternatives to costly practice of planting transplants and the contentious use of herbicide as vegetation management. The second knowledge gap addressed is the need for biomass estimation tools for young afforested plantations. The objectives of this thesis were to bridge the knowledge gaps identified through a comparative study which investigates the relative success of two planting methods (transplanting seedlings and direct seeding), and three vegetation management treatments (annual herbicide application, on-time plastic mulch application and no vegetation control) on the survival/germination and subsequent annual growth and biomass accumulation of bur oak (Ob) (*Quercus macrocarpa* Michx.), red oak (Or) (*Quercus rubra* L.) and black cherry (Cb) (*Prunus serotina* Ehrh.) plantations in southern Ontario. Biomass accumulations are then correlated with height and diameter growth to develop allometric relationships to help predict biomass accumulation. The results of this study are limited by the age of the plantations studied. Although problems that arise in the first years after planting persist over time and grow in severity (Sweeney *et al.* 2007), three years of data collection in forests with rotations greater than 70 years can yield only tenuous conclusions.

LITERATURE REVIEW

AFFORESTATION MANAGEMENT PLANNING

Afforesting abandoned and marginal agricultural lands represents a unique challenge when compared to reforestation in natural settings. Unlike natural forest settings former agricultural lands are exposed to adverse climate conditions, unfavourable soil conditions, unnaturally high levels of weed competition and unnaturally high levels of seed and seedling predation (Cogliastro *et al.* 1997, Sweeney and Czapka 2004, Sweeney *et al.* 2007). Such environmental stressors commonly lead to failed plantations; therefore, mitigating losses from these stressors is imperative. The best way to ensure success is to create a comprehensive, site specific plantation management plan (Allen *et al.* 2001, Sweeney and Czapka 2004, Sweeney *et al.* 2007). Establishing objectives and a budget can help tailor the management plan to achieve the specific short and long term goals of the landowner. Decisions pertaining to site selection, species selection, planting method, site preparation, vegetation management, herbivore management and post establishment monitoring can be tailored to these goals.

Site and Species Selection

The site to be afforested plays a key role in the establishment and eventual success of an afforested plantation. Soil structure and chemistry play a key role in species selection. Soil pH, texture class and nutrient content will determine a site's productivity and the range of species it can support. Species selection will be further constrained by the abiotic and biotic threats to the plantation. These threats include plant competition, animal predation, insect and disease hazards, and potential human hazards introduced by settlement, such as snowmobile trails or adjacent farming operations (De Steven 1991, Stange and Shea 1998, Allen *et al.* 2001, Groninger *et al.* 2004, Sweeney and Czapka 2004, Dey *et al.* 2008).

Using the site description, appropriate crop species can be chosen. Generalist species, such as green ash (*Fraxinus pennsylvanica* Marsh) and American elm (*Ulmus americana* L.), can provide the greatest opportunity for success. Generalist species are more flexible in their site requirements, can quickly occupy sites and can out-compete non-generalist (Groninger 2005). More desirable, high-value hardwoods are often species whose site requirements are very specific (von Althen 1991). Such specialist species are slow growing, leaving them more vulnerable to weed competition and animal predation (Groninger *et al.* 2004). The choice of a generalist or specialist crop tree species depends on the goals for the project and the amount of funding available for vegetation and herbivore management.

Farm fields are subject to a host of unforeseeable events that could hinder the success of a monoculture plantation (Sweeney and Czapka 2004). Subtle differences in soil type, severe insect and disease outbreaks, and variable weathers patterns can lead to significant losses in plantation yield or even plantation failure. Establishing mixed species plantations can mitigate losses, while enhancing a number of other values (Sweeney and Czapka 2004). Mixed species plantations have proven to have higher productivity (von Althen 1991, Pedlar *et al.* 2007), greater biodiversity (Newmaster *et al.* 2006), and improved wildlife and aesthetic values (Twedt and Wilson 2002), when compared to monocultures.

In this study red oak, bur oak and black cherry were selected as crop species. An overview of the critical silvics of each crop species can lead to a better understanding of the results presented.

Red Oak Silvics

Due to its showy grain features and high value, red oak is an ideal candidate for afforestation projects in Southern Ontario. It is a moderate, to fast growing, intermediate shade tolerant tree that grows on dry, well drained soil types (Sander 1991, Cogliastro *et al.* 1997). Site quality for red oak is determined by the depth, texture of the A soil horizon, slope position and shape of terrain (Sander 1991). Sandy littoral deposits provide good growing environment for red oak (Cogliastro *et al.* 2003). Regeneration of red oak is typically sexual however, die back and sprouting occurs as a regular part of the oak's life cycle and helps to build a healthy root system (Auchmoody *et al.* 1994). In order to achieve a healthy root system, die back may happen over many consecutive years, leading to the roots being 10 to 15 years older than the stem (Sander 1991).

Stump sprouting also occurs but, is not conducive to good wood quality and is undesirable (Auchmoody *et al.* 1994). Regenerating red oak naturally is a challenge. Acorn production is quite variable (Auchmoody et al 1994) with some trees always producing a good seed stock and other always producing poor seeds stocks (Sander 1991). In addition to an unreliable seed source, predation severely limits the number of viable seed free to germinate. In poor seasons, up to 100% of a seed crop can be consumed by predators such as squirrels deer and other mammals. Because of predation, it may require up to 500 acorns to produce 1, 1 year old seedlings (Sander 1991). Once germinated, red oak's growth becomes highly dependent on light intensity, growing best in the intermediate crown levels and very poorly in clearcuts (Sander 1991, Buckley *et al.* 1998). When light intensity, soil and nutrient conditions are optimal, red oak has the ability to exhibit episodic flushing which is ideal in a highly competitive environment (Auchmoody *et al.* 1994).

Bur Oak Silvics

Bur oak is an intermediately shade tolerant broadleaf is an early successional species that tends to dominates severe sites (Johnson 1991). Upon germination the tap root penetrates deep into the soil making it very drought resistant and its strong lateral growth enables it to use water efficiently (Johnson 1991). Consequently is intolerant of flooding and highly sensitive to soil water levels (Johnson 1991, Cogliastro *et al.* 2003). Bur oak differs from red oak in having a median position on the soil moisture gradient indicating good growth on a wide range of soil moisture conditions (Cogliastro *et al.*

1997). Like red oak, bur oak is hypogeal but because bur oak has the largest of the native acorns they are susceptible to herbivory and liable to fungal attacks (Johnson 1991). Germination of bur oak usually follows acorn drop, and best on scarified sites where the seed can be in direct contact with the mineral soil (Johnson 1991). Bur oak's resilient growth characteristics make it a good species to use in the harsh environment that afforestation projects present.

Black Cherry Silvics

Black cherry is a rapidly growing species that typically grows quicker than oaks in the first growing season (Farmer 1980). Black Cherry is more frost resistant than other species making it a potential species for afforestation (von Althen 1991). It is an early successional shallow rooting species that is shade intolerant upon maturity but requires a heavy canopy for germination (Marquis 1991). Stump sprouting is common and some of the sprouts can end up producing lumber quality wood (Marquis 1991). Like red oak, some trees never produce an abundance of seed where as other always do (Marquis 1991). Problems with the establishment of black cherry from seed include: predation from rodents, birds and deer and to the drying out of seeds before germination (Huntzinger 1967). Direct exposure to sunlight is not conducive to germination indicating that clearcutting is not an acceptable harvest method without sufficient advanced regeneration (Marquis 1991). Site preparation is not required as it has no significant effect on the germination of black cherry (Huntzinger 1967). Once seed are shed they will remain in a seedbank for up to 3 years waiting for the optimum germination environment (Marquis 1991). Moisture is an important factor in seed germination and thus it is important to bury the seeds a few inches in the ground to keep them moist (Huntzinger 1967). Upon germination black cherry has the potential to grow up to 10 centimetres in a matter of 30 days (Marquis 1991). Black cherry is a generalist species that can grow on a variety of soil types so long as the summer growing conditions are cool and moist (Marquis 1991). It can tolerate a variety of drainages but its productivity decreases with wetter conditions (Marquis 1991). Black cherry prefers strongly acidic soil and poorly productive sites with a high coarse fragment content and is a suitable candidate for afforestation activities (Marquis 1991).

Planting Method

When afforesting marginal farm lands, there are two main artificial regeneration methods to consider: (1) planting nursery stock, and (2) direct seeding. Each method has its own set of advantages and disadvantages. Depending on the objectives, budget, site characteristics and desired crop species one option may be more desirable than the other.

Planting nursery stock has been the traditional afforestation practice throughout North America and has held as a more reliable regeneration technique that provides greater success when compared to other methods (von Althen 1997). The established root systems enable the seedlings to effectively take advantage of optimum growing conditions and out-compete other vegetation (Twedt and Wilson 2002, Willoughby *et al.* 2004). Stock quality plays an important role in enhancing the growth of tree seedlings. Planting large, high grade nursery stock with a high concentration of fibrous roots will improve crop tree survival and growth (Gordon 1988). In general planting is a costly regeneration method that carries a high risk if the plantation fails. Nursery stock plantations would typically be managed for high yield and value when harvested (von Althen 1991).

Direct seeding is a contentious practice that has met much scepticism. The benefit of direct seeding is that it can save 50-66 percent of the total establishment cost when compared to planting (Allen *et* al. 2001, Löf and Welander 2004, Dey *et al.* 2008). Direct seeding also has a very flexible window for seed sowing, which allows seeding later in the season when planting seedlings would be ineffective (Johnson 1981, Timmons *et* al. 1993, Pijut 2003, Dey *et* al. 2008). Despite its appeal as a cheap and flexible regeneration technique, direct seeding produces uncertain germination rates and germination is often poor (von Althen 1997, Dey and Buchanan 1995, Nilsson *et al.* 1996, Willouby *et al.* 2004, Dey *et al.* 2008). In addition, directly seeded trees because of their slow growth are vulnerable to weed competition and herbivore damage for an extended amount of time. This can lead to increased uncertainty in final plantation densities and reduced productivity (Dey and Buchanan 1995, Willoughby *et al.* 2004, Edge 2004). In the end, mitigating seedling losses often makes direct seeding no less expensive than planting (Dey and Buchanan 1995). If the risk of plantation losses can be minimized in a cost effective manner, direct seeding can provide landowners with the opportunity to meet their ecological and aesthetic objectives at a relatively low cost. With more research into the specific limitations of direct seeding, landowners will be able to assess their objectives and make an educated judgement about whether or not direct seeding is appropriate for their needs.

Site Preparation and Weed Control

Control of aggressive weed growth in afforested plantations is essential for success (von Althen 1991, Sweeney *et al.* 2007). Fast growing herbs and shrubs compete with crop trees for water, nutrients, growing space and light. Initial site preparation removes herbivore habitat, while controlling unwanted vegetation (Dey and Buchanan 1995, Edge 2004). Enhanced vegetation control after crop tree establishment can be accomplished through chemical, mechanical, biological and manual methods.

Mechanical site preparation is the most common means of controlling competing vegetation prior to plantation establishment. Abandoned agricultural fields can be disked and ploughed to loosen compacted soil, remove herbivore habitat, increase soil temperatures and delay herbaceous competition (von Althen 1991, Dey and Buchanan 1995, Nilsson *et* al. 1996, Allen *et al.* 2001, Groninger *et al.* 2004). Subtle fluctuations in water levels can also be manipulated using mechanical site preparation (Allen *et al.* 2001). Although its benefits are short term, mechanical site preparation improves planting efficiency, simplifies site designs and acts as an effective vegetation management tool.

There is a variety of forestry grade herbicides used to control specific groups of crop tree competitors. Glyphosate is a non-selective systemic herbicide that can be absorbed through the leaves of a plant, killing it within 14 days (Monsanto Canada 2007). As a site preparation tool, it can be applied as a broadcast spray during the fall prior to spring planting (von Althen 1991). Glyphosate can also be applied in the spring before planting, before leaf flush to kill competitors, or even during the early summer, provided crop trees are protected from herbicide drift (Monsanto Canada 2007). Simazine is a persistent herbicide that targets broad leaved trees and grasses by entering through their roots (Synergenta Canada 2007). Simazine can be applied to a site in the fall without shielding crop trees (von Althen 1991). Post establishment herbicide application can be useful in controlling perennial vegetation. Combining mechanical site preparation with herbicide application can produce excellent results (von Althen 1991). In order to provide adequate protection against weeds, herbicide should be applied for the first two to five years after planting (Dey *et al.* 2008).

Herbicide application is a cheap and effective method for preparing a site for planting and controlling competing vegetation post-establishment. However, herbicides are coming under increased criticism from an environmental perspective. Alternatives to herbicide use for post-establishment weed control are available and can successfully accomplish the same goals as herbicide. Biological control methods such as planting cover crops have been used to create environments free of aggressive competitors, while providing the opportunity to enhance the soil nutrient environment (von Althen 1991). More research into the use of cover crops is needed to determine their capacity to improve crop tree growth (Willoughby *et al.* 2004). Mowing between rows is a standard vegetation control method in afforested plantations; however, its effectiveness is debated (Johnson 1981, Löf and Welander 2004). Commonly used successful alternatives to herbicides also include organic and plastic mulches.

Organic mulches can be derived from a variety of products. Sawdust, wood chips, bark, peat moss, hay and straw are used to form protective barriers around crop trees (von Althen 1991). Organic mulches have limited success in improving crop tree growth due to lowered soil temperatures under the mulch (von Althen 1991, Traux and Gagnon 1993). Plastic mulches have superior qualities and provide a variety of benefits to crop trees beyond that of vegetation control. Black plastic mulch has the ability to prevent leaching and soil erosion by acting as a barrier from heavy rain. The mulch retains water longer than unprotected soil, making the micro-site more resistant to drought (Traux and Gagnon 1993). Its ability to retain water, increase soil temperature and improve growing conditions encourages extended growth in the early growing season and helps crop trees establish dominance over weedy competition (Bowersox and Ward 1970). However, if the soil under the mulch does dry out, it will take longer to re-saturate it, making the seedling more susceptible to drought stress. Plastic mulch costs much more than a single application of herbicide, but in the event that the landowner prefers not to use chemical weed control, mulching can be an effective alternative.

Herbivore Control

Herbivores have been identified one of the most difficult factors influencing the success of afforested plantations, especially when direct seeding is used (von Althen 1991, Willoughby *et* al. 2004, Sweeney *et* al. 2007). Weeds and mulching provide habitat for small mammals that prey on seeds and girdle trees (Traux and Gagnon 1993). Small mammals and birds are a concern for plantation managers, but large-bodied herbivores, such as white-tailed deer (*Odocoileus virginianus* Boddaert), pose the greatest risk to plantation health (Huntzinger 1967). White-tailed deer populations are often very high in agricultural areas (Sweeney *et al.* 2007) and their influence on crop tree growth can mask the influence of other critical site factors (Sweeney and Czapka 2004).

Most herbivore control methods are expensive and should be applied according to the apparent risk of plantation failure (Allen *et al.* 2001). Poison baits and repellents have been used to eliminate rodent and avian predators with minimal success (Dey and Buchanan 1995). Physical barriers such as tree protectors, metal screens and electric fencing do discourage animal damage to plantations, but they are expensive and require continual maintenance in order to be effective (Anonymous 2001, Dey *et al.* 2008).

One of the best approaches to mitigating animal damage to seeds and seedlings is to understand the herbivore populations at the site and adjust management plans and study designs to accommodate them. The greatest amount of predation will occur in years of peak mammal populations, and predation will be greatest under forest cover or near forest edges (Johnson 1983, Jacobs and Wray 1992, Dey *et al.* 2008). Therefore, establishing plantations in large openings far away from the forest edge (>60 m) may result in reduced herbivore impact (Clatterbuck 1997, Dey *et al.* 2008).

Post Establishment Monitoring and Adaptive Management

Afforesting marginal agricultural lands regardless of the motivation is a process that involves a considerable amount of temporal and financial investment in order to accomplish a set of management goals. Developing a monitoring program, whether it is extensive or intensive, may be the most important part of successful plantation management (Allen *et al.* 2001). Using the adaptive management process (Reever

Morghan *et al.* 2006), elevated risks of flooding, peak weed competition, animal predation and severe insect and disease outbreaks can be appropriately dealt with prior to severe losses (Allen *et al.* 2001). In addition, continual monitoring can track the progress and eventual achievements of the management goals and enable the landowner to incorporate new management goals as they arise.

Overcoming the Challenges to Afforestation

Making the correct choices during the initial stages of an afforestation project is vital to the success of the plantation. Often, problems that arise in the first years after planting persist over time and grow in severity (Sweeney *et al.* 2007). The importance of forethought is crucial as it may 30 years before a plantation failure is evident (Carter *et al.* 1984). Often, afforestation projects fail because of poor management decisions or lack of a management plan. Afforestation is challenging and can prove to be expensive; therefore, it is unwise to underestimate the importance of planning to ensure success. To mitigate failure, it is important to identify the previous management regimes and the crucial site factors in the short and long term.

QUANTIFY.ING TREE BIOMASS THROUGH ALLOMETRIC RELATIONSHIPS

When biomass accumulation is a management objective, providing accurate estimations is a necessity. Estimating the total biomass in a new forest requires an estimate of total dry weight biomass and true values can only be obtained through destructive sampling of the above and below ground components. Obtaining dry weights, especially for the roots is a laborious task and is impractical for every plantation. To eliminate this process destructive sampling can be conducted on a representative sample of a species in a large geographic area and allometric relationships can be developed to reliably predict tree biomass using easily measured variables. This process has proven to be an accurate and useful tool throughout the literature (Niklas 1994, Ter-Mikaelian and Korzukhin 1997, Ketterings *et al.* 2001). Allometric equations predicting shoot biomass in mature stands in North America have been well published (Ter- Mikaelian and Korzukhin 1997, Gardiner and Hodges 1998, Wagner and Ter-Mikaelian 1999). Root biomass equations have received less attention (Drexhage *et al.* 1999, Bond-Lamberty *et al.* 2002, Knapp *et al.* 2006) and there are even fewer studies focusing on allometric relationships in tree seedlings (Wagner and Ter-Mikaelian 1999, Bond-Lamberty *et al.* 2002). General allometric equations can be applied to a variety of species in varying regions to estimate biomass at a landscape level (Carins *et al.* 1997), but species specific equations can provide a more precise estimate (Ketterins *et al.* 2001).

Biomass allocation between the roots and the shoots varies with stand age (Gerhardt and Fredriksson 1995). During stand development root-to-shoot ratios vary with microsite conditions (Gerhardt and Fredriksson 1995). When seedlings are in resource limited environments root biomass allocation is favoured over shoot biomass to enhance the seedling's capacity to take up water and nutrients, provide structural support and improve its survival (Coutts 1983, Vitousek and Sanford 1986, Kolb and Stiener 1990, Edelin and Atger 1994, Carins *et al.* 1997, Gardiner and Hodges 1998, Drexhage *et al.* 1999, Danner and Knapp 2001). The inherent variation in root-to-shoot ratio throughout the stages of tree development suggests that allometric equations are only relevant for short periods of time (Kolb and Steiner 1990). Allometric equations derived from mature forests may inadequately describe the biomass being accumulated in young afforested plantations and biomass estimates for such plantations would be flawed. Therefore the need for specific allometric equation for juvenile plantation development is evident.

METHODS

SITE SELECTION AND DESIGN

Site selection was a fixed variable in this experiment and three sites were chosen deliberately based on their geographic location (Figure 1), size and soil conditions. The Pittock Conservation Area (Lat 43.184, Long 80.707) is located 10 km northeast of Woodstock Ontario and is a publically owned property managed by the Upper Thames Conservation Authority. The study site was located within a productive agricultural field leased by the conservation authority to local farmers for crop production. The site is directly adjacent to a freight rail line, a small woodlot, and a manicured arboretum. The terrain mildly slopes to the east towards the railway tracks. The Fingal Wildlife Management Area (Lat 42.681, Long 81.326) is located 10 km southwest of Fingal Ontario and is a publically managed, multi-use use area. The property includes a large wooded area used as a recreational facility as well as a number of large fields leased to farmers for crop production. The study site in this area was located in a remote field along a drainage buffer, with two edges adjacent to the forest, the third adjacent to a brush row and the final edge adjacent to a crop field. The terrain is flat and located in a low lying area prone to spring flooding. The Littlejohn Farm site (Lat 42.620, Long 81.384) is a privately managed property located approximately 15 km southwest of Fingal, Ontario. The terrain is rolling, with a thick row of spruce trees adjacent to the north boundary of the site, approximately 0.04 ha of which were included within the confines of the study area.

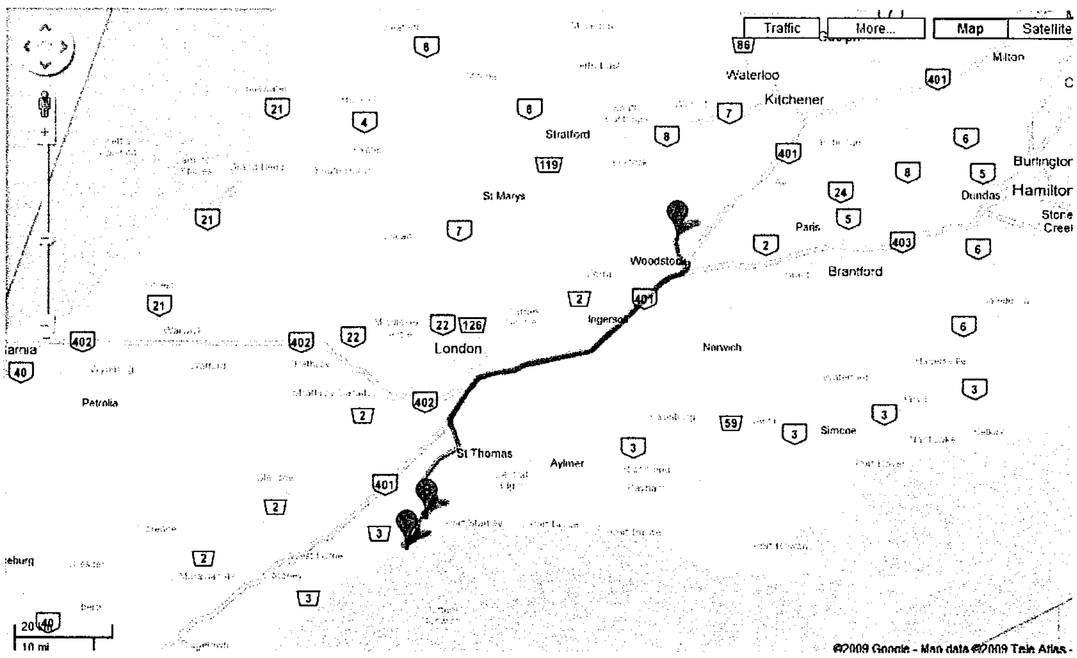


Figure 1. Map of southern Ontario indicating the location of a) Pittock Conservation Area b) Fingal Wildlife Area and c) Littlejohn Farm.

All sites were approximately 1 ha in size and completely enclosed by an electric fence operated by a solar powered car battery to discourage herbivore damage. Three soil samples of approximately 5 kg were taken from the upper slope, mid-slope and lower slope areas at each site. Soil physical, chemical and nutrient analyses (Appendix I) were conducted Lakehead University's Soils Testing Laboratory in Thunder Bay Ontario. Sites were prepared by disking and ploughing the fall prior to planting followed by a broadcast herbicide application around each study plot and the fence line to limit weed in-growth. Spaces between rows are mowed once a year to reduce weed growth and animal habitat and improve access as per standard plantation management procedures in that area.

SPECIES SELECTION

Crop tree species were selected in consideration of a number of factors. Oaks are well adapted to the southern Ontario environment and their populations have been declining in the area thus they have been a popular species in afforestation projects. Their large acorns make seed collection and direct seeding relatively easy. The acorns make valuable forage enhancing wildlife habitat and the raw timber is valuable making it even more desirable crop species. Black cherry was chosen because, unlike the oaks, it is a pioneer species with small seeds. It is not as widely used as a crop tree species in afforestation projects and it is rarely used in direct seeding because of its inconsistent germination rates. Black cherry showed some potential for a cheap seed source that may excel.

VEGETATION MANAGEMENT AND APPLICATION

Vegetation management treatments were applied to whole plots randomly within each site. Herbicide plots were treated with a low volume foliar herbicide once a year to control competing vegetation and the product used, and application rates varied between sites and seasons. Simazine was applied to all three sites in May of 2006 at a rate of 5.68

kg ha^{-1} at the Pittock site and 7.80 kg ha^{-1} for the other two sites. A second application occurred in November of 2006 for the Fingal and Littlejohn sites and in April 2007 at the Pittock site at a similar rate to the first. A third application of simazine was applied with a 1% glyphosate solution in October of 2007 at an application rate of 11.00 kg ha^{-1} at the Fingal and Littljohn sites. Glyphosate was added to the herbicide application to provide improved control over aggressive weed competitors while providing the residual effect of the simazine. The third simazine application for the Pittock site was conducted in April of 2008 at an application rate of 5.50 kg ha^{-1}.

Green plastic mulch was used as a one-time application following site establishment in the summer of 2006. Green polyethylene mulch was cut into 1 m^2 pieces, perforated in the middle and placed over the planted seedling or the directly seeded planting location. The sheets of mulch were then pegged down using 8, 20 cm long research pins. Control plots were established without any vegetation management.

PLANTING METHOD

Seeds were collected by volunteers with the Stewardship Council and the Conservation Authority in the fall of 2005, sealed in plastic bags and refrigerated overwinter. Oak seeds were planted at a depth of 2 cm at a density of 3-5 seeds per planting location. The smaller black cherry seeds were planted at a density of 10-15 seeds per location. The planted stock was purchased from a local nursery and stock type varied to accommodate availability. The planted red oaks were bare root 2+0 stock, and the bur oak and black cherry were 1+0. Although stock age varied, they represent the type of stock typically used in afforestation projects in the area and best suited the long-term goals of this study. The direct seeding and planting was conducted by volunteers the following spring from April 30th to May 6th.

HERBIVORE ASSESSMENT

An indirect assessment of herbivore populations was conducted through the accumulation of local and historical knowledge for the study sites. General consensus was that white-tailed deer populations were high and significant tree mortality would likely be incurred unless access was restricted to the plots. As a result the electric fence was erected along the perimeter of the study site. Also, small seed predators such as voles were identified as potential hazards to directly seeded plots, especially those directly adjacent to the forest edge. Thus, seeds were buried to a depth of 3 cm to make the seeds more difficult to detect.

A post establishment herbivore assessment was conducted in the fall of 2008 at the Littlejohn site to identify specific herbivore species. This area was chosen due to the apparent high risk of predation and the poor germination results in close proximity to the spruce trees presumably a result of seed predation. White pieces of shelving paper were pegged into the ground, sticky side up, directly adjacent to the spruce outcrop within the study site. The outer 4 cm on the perimeter of the shelving paper was dusted with black chalk to act as marking ink and the remainder of the paper was left blank to act as a track recording sheet. A small opening was cut out of the middle of the shelving paper and oak seeds were placed in a shallow hole to act as bait (Figure 2). Herbivores attracted to the bait stepped on the chalk and left a track on the marking paper, which was easily identifiable at the genus level, and most times at the species level. Track plates were left out for three consecutive nights in the fall of 2008 and checked in the early morning after the third night.

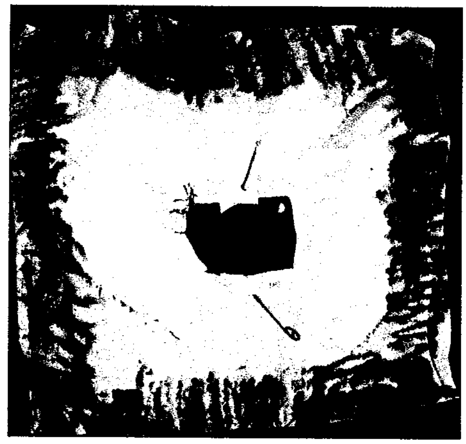


Figure 2. Track plate with a centre hole to facilitate baiting.

STUDY DESIGN AND EXECUTION

The plantation study was a 2x3x3 factorial experiment with two planting types (direct seeding and planting seedlings), three vegetation management treatments (no treatment, one-time plastic mulch application and annual herbicide application), and three tree species (bur oak, red oak and black cherry) (Figure 3). Treatments consisted of 15 planting spots arranged in a $100m^2$ plots. Trees were planted in rows with a 2 m within row spacing and a 3 m between row spacing. Each plot was replicated three times at three different sites. Replications were applied randomly at the site level, which expanded the inference space or the results beyond the specific locality of the study sites.

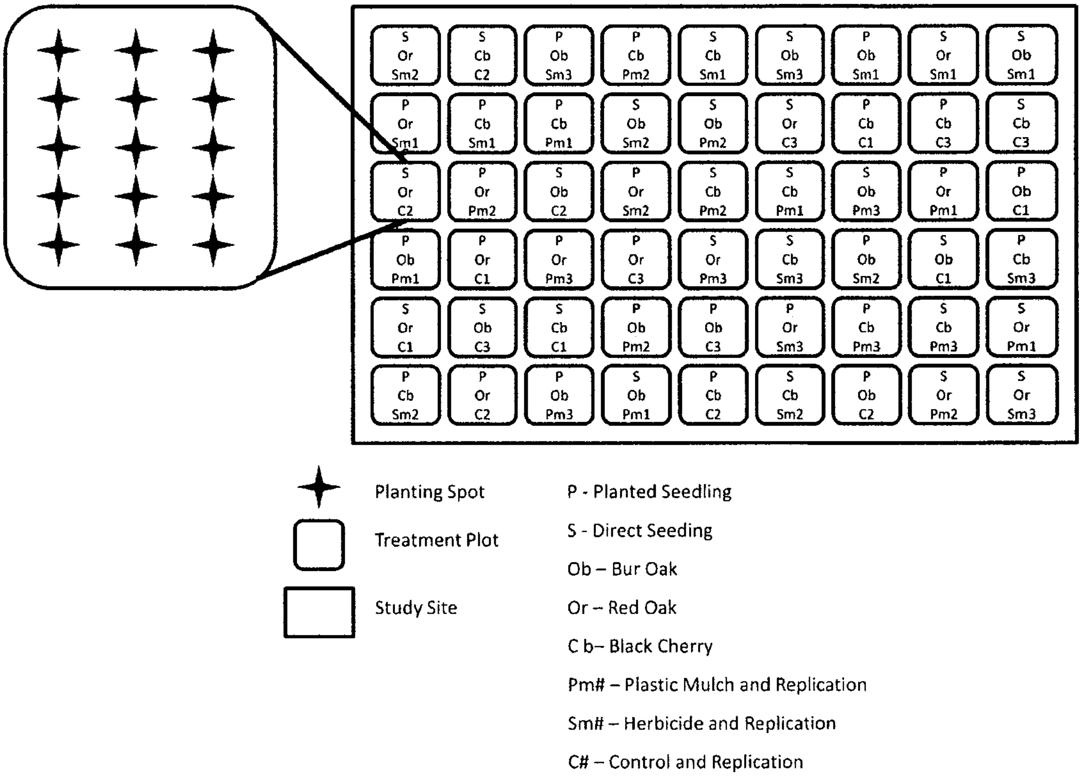


Figure 3. Diagram illustrating the random allocation of treatment combinations to the 54 plots within each study site.

DATA COLLECTION

Germination, Survival, Height and Root Collar Diameters

Germination, survival and seedling heights were collected for all planting locations in the spring and fall of each year from 2006 to 2008. Germination and survival were calculated by dividing the total number of healthy seedlings by the total number of planting spots that were potentially occupied for each measurement interval.

Height increments were calculated by subtracting the previous fall`s height estimates from the current fall`s height estimates on the same trees. The 2006 increment for planted seedlings used spring 2006 height data as the base. Root collar diameters (RCD) for living trees were collected from one random plot from each treatment combination at each site in the fall of 2006 (Appendix II) and 2008. RCD measurements were collected using digital calipers placed flush with the soil.

Biomass Accumulation

During the fall of 2008 complete trees from each planted and directly seeded plot containing more than two oak trees were harvested in both planting treatment. The number of seedlings of each treatment combination can be found in Table 1. Black cherry was not harvested due to its poor seed germination results and plots with fewer than two trees were left untouched to preserve the integrity of the growth and development study. Trees were excavated using a spade shovel and roots were carefully removed from the soil to ensure the maximum amount of root material was retrieved. Obtaining fine root samples was not possible using this method thus the root biomass reflected in this paper represents a conservative estimate including coarse roots only. Seedlings were separated into their root and shoot components and dried to a constant weight at 80°C (West 2009). Root and shoot weights were measured on a digital scale and total biomass was calculated from the sum of the root and shoot weights.

Table 1. Count of seedlings harvested for biomass analysis by treatment combination.

Planting Method	Species	Control			Herbicide			Plastic Mulch			
		Littjohn	Fingal	Pittock	Littjohn	Fingal	Pittock	Littjohn	Fingal	Pittock	Total
S	Ob	6	6	6	6	6	6	2	4	6	48
S	Or	6	6	6	2	6	6	2	6	4	44
P	Ob	4	4	8	6	8	6	6	6	6	54
P	Or	6	2	4	6	2	6	6	6	8	46
Total		22	18	24	20	22	24	16	22	24	192

STATISTICAL ANALYSIS

<u>ANOVA</u>

Univariate ANOVA's were conducted for the 2008 RCD, shoot biomass, root biomass, total biomass and root-to-shoot ratio measurements. Repeated measures ANOVAs were conducted on germination, survival, total height growth and annual height increment data. All ANOVA designs were unbalanced as a result of differences in survival and the field layout of the study design. As a result the Type III sums of squares were used to account for differences degrees of freedom among treatment combinations. The analysis was conducted first on the full data set and was then subdivided into planting method specific datasets to remove some of the variance introduced by the sizeable difference between planted and directly seeded trees after three years. Differences among species were analyzed using a Scheffe *post hoc* test.

Non-linear Regression

Biomass accumulation was correlated with total height growth and total root collar diameter measurements three years after plantation establishment. A curve estimation procedure was used to identify which regression modeling technique best described the data. Non-linear regression provided the best estimate of seedling biomass accumulation patterns. A power function ($Y=a*x^b$) was used to relate RCD and height measurements to shoot, root and total biomass accumulation. ANOVA was used to test the strength of height and root collar diameter as predictors and identify the value in using two predictor variables instead of one. Biomass equations were then tested against datasets for other biomass components using an F-test to see if a single equation could be used for all biomass components

Economic Data and Summary Model Development

Tree seedling costs were obtained from the Ferguson Forest Tree Nursery in Kemptville Ontario. Tree seed costs were obtained from the Ontario Angus Tree Seed Facility catalogue. Labour and capital costs were estimated based on historical operational costs common in the southern Ontario area obtained through the Oxford

Stewardship Council and the Upper Thames Conservation Authority. A breakdown of plantation establishment costs is found in Table 2.

Table 2. Estimated cost per unit for establishing afforested plantations.

Event	Cost	Unit
Site Preparation	60	$/ha
Plastic Mulch	405	$/ha
Herbicide	60	$/ha
Electric Fencing	5000	$/ha
Or Nursery	0.8	$/seedling
Ob Nursery	0.8	$/seedling
Cb Nursery	0.8	$/seedling
Or Seed	72	$/1000 seeds
Ob Seed	49	$/1000 seeds
Cb Seed	11	$/1000 seeds
Wage for Seeders	15	$/hr
Cost Machine Plant	150	$/hr

The summary tool is simply an aggregation of data observed in this study scaled up to a hectare level. Each treatment had a specific germination and survival rate and that rate multiplied by the initial planting density yields the number of stems per hectare after three years. Each treatment combination also had a unique average height and root collar diameter after three years. Using the biomass equations those average measurements were translated in shoot, root and total biomass accumulations. Multiplying the single tree biomass estimate by the total stems per hectare yields a total biomass accumulated per hectare.

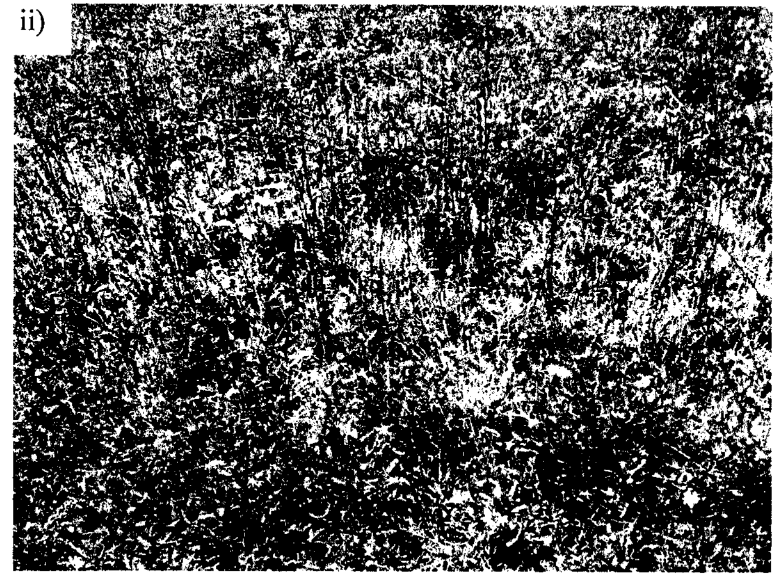
RESULTS

COMPETING VEGETATION

All study sites were dominated by dense populations of goldenrod (*Solidago* spp.), joe pye weed (*Eutrochium* spp. Rrafinesque) and wild carrot (*Daucus carota L.*) approximately 1.5 m in height. Although no formal assessment of the influence of vegetation management was made on competing vegetation Figure 4 demonstrates the unique impact each vegetation treatment had on competing vegetation.

i)

ii)



iii

Figure 4.Photographs showing: i) control plot;, ii) herbicide plot; and iii) plastic mulch plot.

HERBIVORES

Raccoons (*Procyon lotor* L.) were the most prevalent herbivore at the Littlejohn site. Track evidence (Figure 5a) and evidence of digging around other planting plots suggest that raccoons were attracted to the buried red oak seeds. Although racoons were the only species on the track plates, moles (Subfamily-Scalopinae) were seen on the site and burrowed around the plastic mulch (Figure 5b), suggesting they were another significant source of herbivore damage.

Figure 5. Examples of herbivore activity: i) raccoon track marked on tracking plate and ii) holes created by moles borrowing under plastic mulch.

PLANTATION ESTABLISHMENT, GROWTH AND DEVELOPMENT

Planted Seedling Survival

Both species (p=<0.001) and vegetation management (p=0.037) had a significant effect on seedling survival for planted seedlings over three years (Table 3). Planted seedlings survival decreased over time with red oak recording the highest survival rate and bur oak recording the lowest (Figure 6). Under plastic mulch survival percentage was higher for all three species: Cb (76%), Ob (56%), and Or (90%). Bur oak produced the most variable results ranging from 34% survival in the control plots to 56% survival in the plastic mulch plots.

Table 3. ANOVA results for seedling survival tested by species and vegetation management. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ^{ns} indicate non-significance.

Source	df	Mean Square	F	p-value
Species	2	2.282	22.287	<0.001***
Vegetation Management	2	0.353	3.448	0.037*
Species x Vegetation Management	4	0.120	1.170	0.331^{ns}
Error	71	0.102		

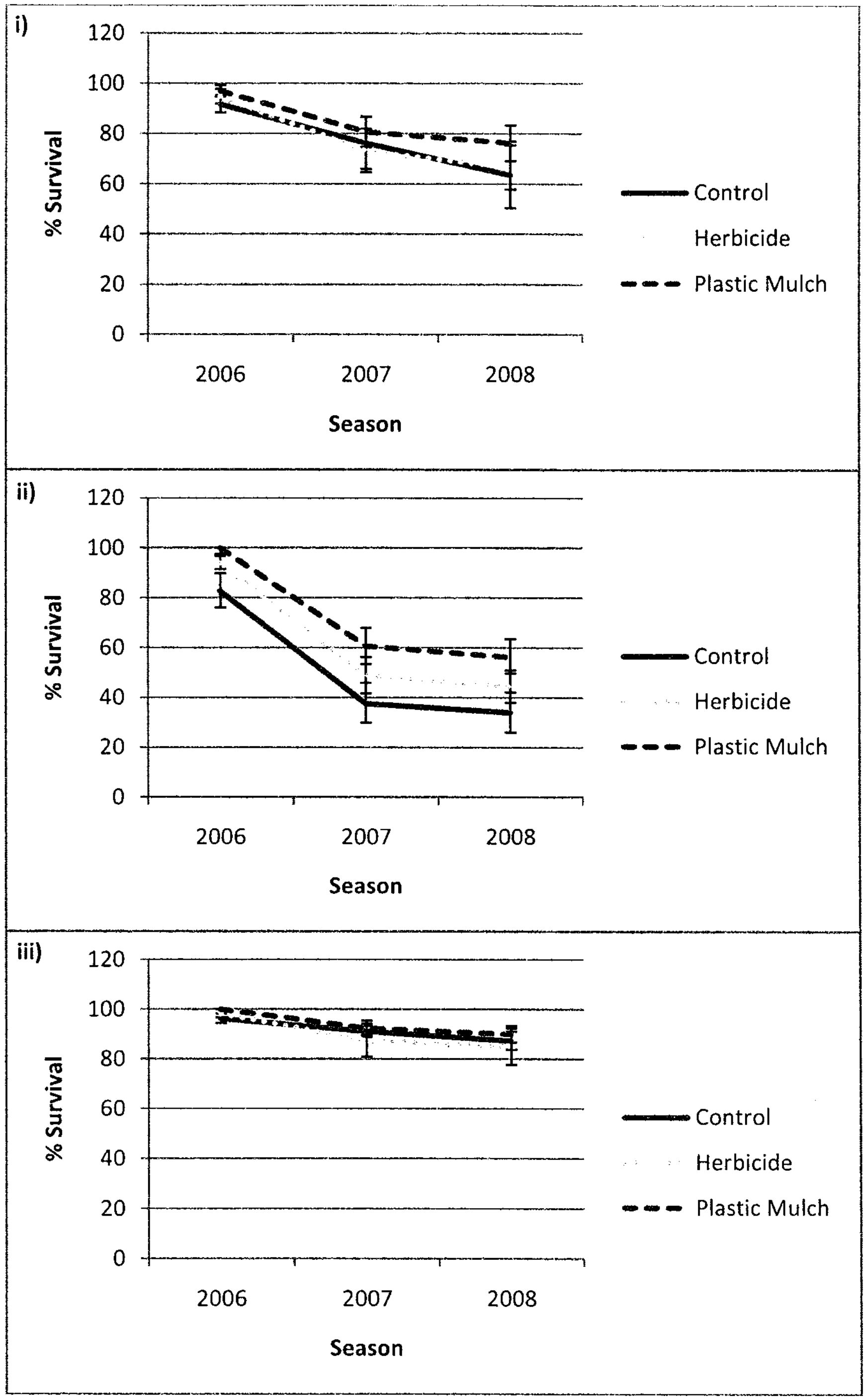


Figure 6. Proportional survival of transplants three seasons after planting i) black cherry, ii) bur oak, and iii) red oak with different vegetation management regimes. Bars show area within one standard error of the mean.

Germination

Germination was highly variable within species and vegetation management treatments and differences among these factors made it difficult to develop valid statistical tests to detect statistical differences. The highest variation occurred in black cherry plots (Figure 7) where germination was between 10% and 32%, germinating best under the plastic mulch. Oak did not germinate well under the plastic mulch. Bur oak germinated well in the herbicide and control plots with 77% and 89% of total planting spots occupied after three years, respectively. Red oak had the greatest germination proportion and the most consistent results for vegetation management. The control and herbicide treatments germinated at 89% and 85%, respectively, and the plastic mulch at 68%.

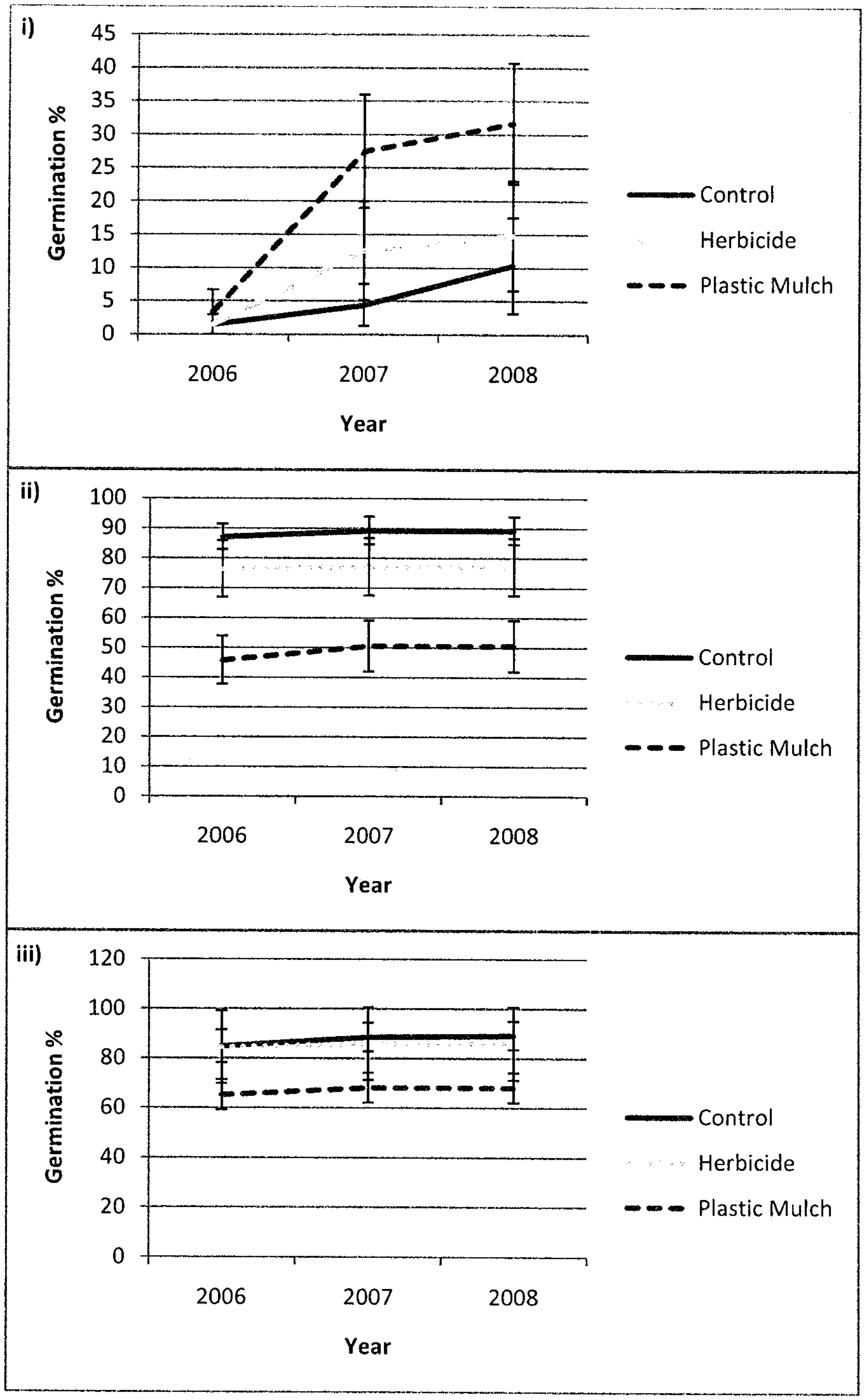


Figure 7. Proportional germination of directly seeded seedlings three seasons after establishment i) black cherry, ii) bur oak, and iii) red oak with different vegetation management regimes. Bars show area within one standard error of the mean.

Growth and Development Model

All main effects in the model produced very highly significant different results (p=<0.001) (Table 4). Directly seeded seedlings had significantly less height growth than planted seedlings. Bur oak had significantly lower total height than red oak and black cherry. The control produced significantly less total height than the plastic mulch and herbicide treatments. The large difference in growth rates between the planting method created noise in the analysis which interfered with detecting the true interactions between treatment combinations. Therefore, the dataset was split into two groups based on planting method.

Table 4. Repeated measures ANOVA results for the complete model comparing planting method, species and vegetation management. * indicates significance at $\alpha=0.05$, ** indicates significance at $\alpha=0.01$, *** indicates significance at $\alpha=<0.001$ and ns indicate non-significance.

Source	df	Mean Square	F	p-value
Planting Method	1	2099757	1055.621	<0.001***
Species	2	127896.4	64.298	<0.001***
Vegetation Management	2	14867.74	7.475	<0.001***
Planting Method x Species	1	126672.2	63.683	<0.001***
Planting Method x Vegetation Management	2	3709.235	1.865	0.155ns
Species x Vegetation Management	4	1844.959	0.928	0.447ns
Planting Method x Species x Vegetation Management	2	1047.248	0.526	0.591ns
Error	1292	1989.12		

Planted Seedlings

Planted seedlings were able to perform well in the open field environment. Total height varied significantly among species (p=0.001) and vegetation management (p=0.004) (Table 5). Black cherry (Figure 8) proved to accumulate the greatest total height. The oak species grew characteristically slow, more so bur oak than red oak. Total oak height remained relatively constant until the 2008 growing season. By fall 2008 the average red oak was about 80 cm in height, statistically similar to black cherry, while bur oak accumulated less than 50 cm of growth. Total height was significantly improved in the plots where vegetation management was used. Both plastic mulch and herbicide had similar positive effects on the total height of all three species. The control treatment produced inferior results even from the start of the study.

Table 5. Repeated measures ANOVA results for total height growth of planted seedlings comparing species and vegetation management. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ^{ns} indicate non-significance.

Source	df	Mean Square	F	p-value
Species	2	149627.9	45.04	<0.001*
Vegetation Management	2	18641.2	5.611	0.004*
Species x Vegetation Management	4	2298.202	0.692	0.598
Error	768	3322.114		

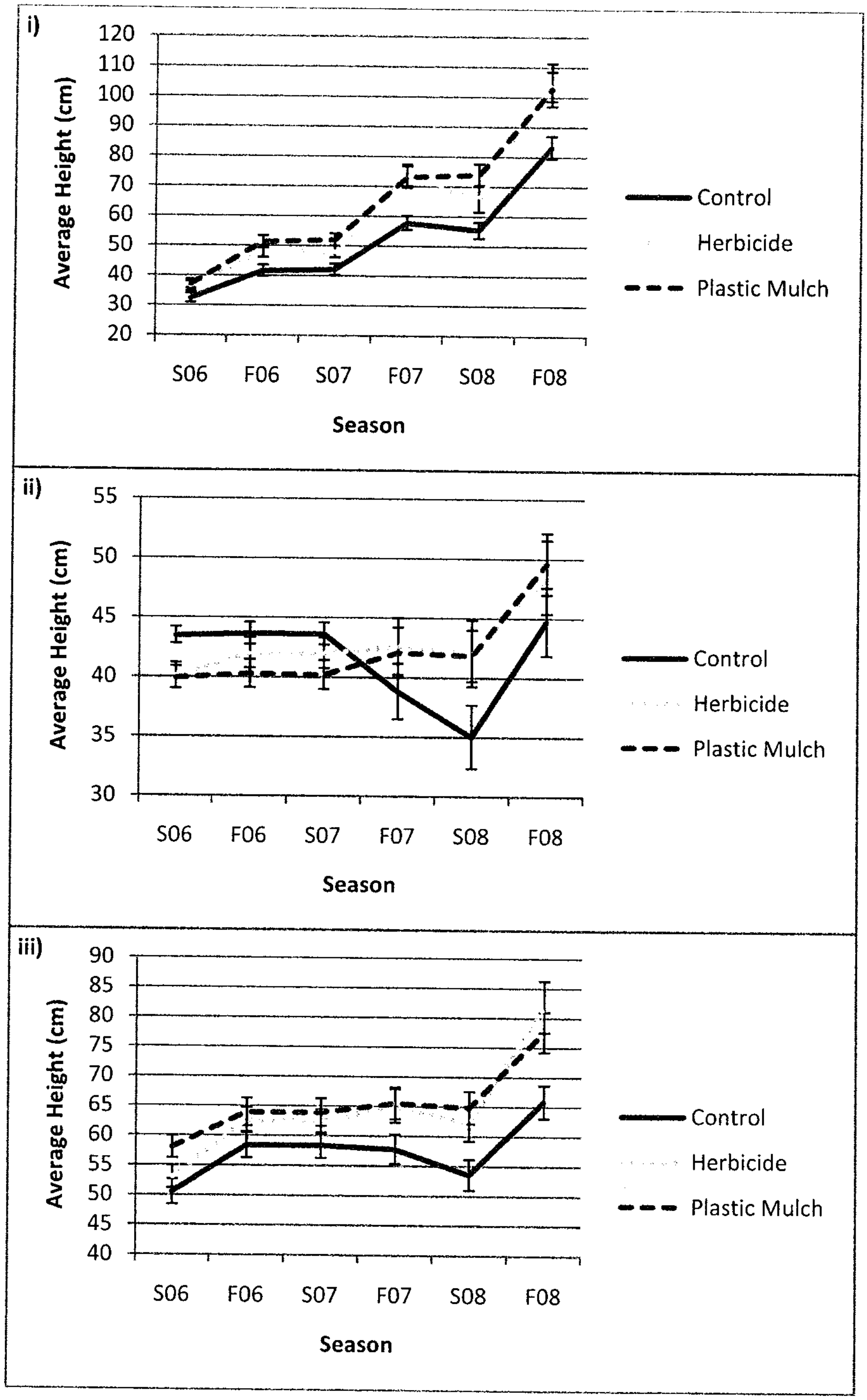


Figure 8. Average height growth for planted seedlings with different vegetation management three years post establishment i) black cherry, ii) bur oak, and iii) red oak. Bars show area within one standard error of the mean.

The height increment for planted seedlings shows more complex trends. Both species (p=<0.001) and vegetation management (p=<0.001) produced significantly different results (Table 6). Black cherry (Figure 9) had the greatest average annual height increment over three years, while bur oak had the least average annual height increment. Herbicide plots produced the greatest height increments and those increments were statistically similar to the increments seen in the plastic mulch plots, but different from the control plots. The control plots and the plastic mulch plots produced similar results.

Table 6. Repeated measures ANOVA results for annual average height accumulation comparing species and vegetation management. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ^{ns} indicate non-significance.

Source	df	Mean Square	F	p-value
Species	2	33523.05	80.466	<0.001***
Vegetation Management	2	2904.97	6.973	<0.001***
Species * Vegetation Management	4	1686.816	4.049	0.003**
Error	659	416.612		

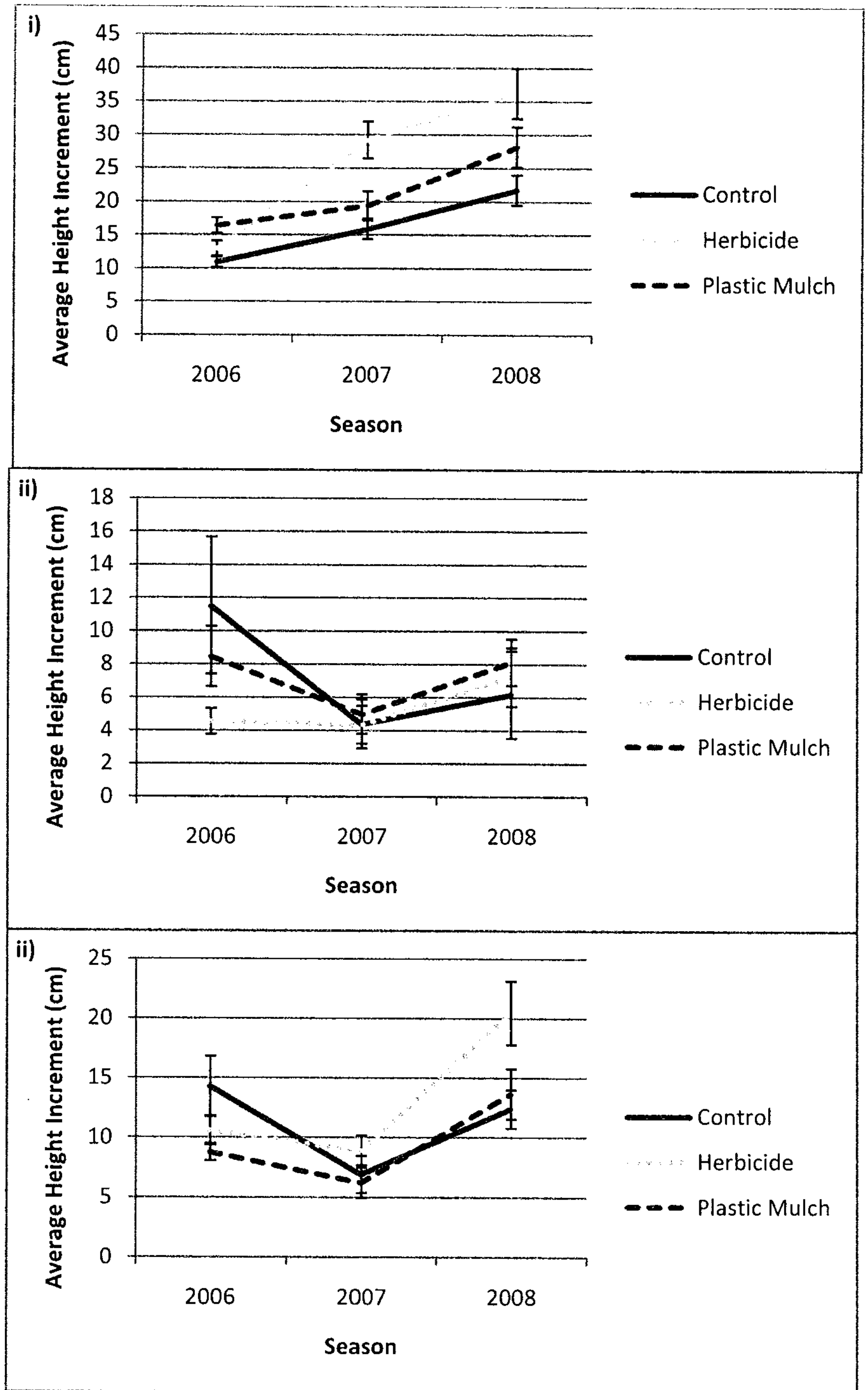


Figure 9. Average annual height increment planted seedlings with different vegetation management three years post establishment i) black cherry, ii) bur oak, and iii) red oak. Bars show area within one standard error of the mean.

Root collar diameter in planted seedlings was different for each species and vegetation control treatment (Table 7). Black cherry (Figure 10) accumulated the greatest RCD by fall 2008, significantly greater than both oaks. Vegetation management had a positive effect on RCD for both treatments.

Table 7. ANOVA results for RCD growth of planted seedlings with different vegetation management harvested three years after establishment three years post establishment. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ns indicate non-significance.

Source	df	Mean Square	F	p-value
Species	2	407.002	7.345	<0.001***
Vegetation Management	2	293.993	5.305	0.005**
Species x Vegetation Management	4	105.244	1.899	0.110ns
Error	303	55.414		

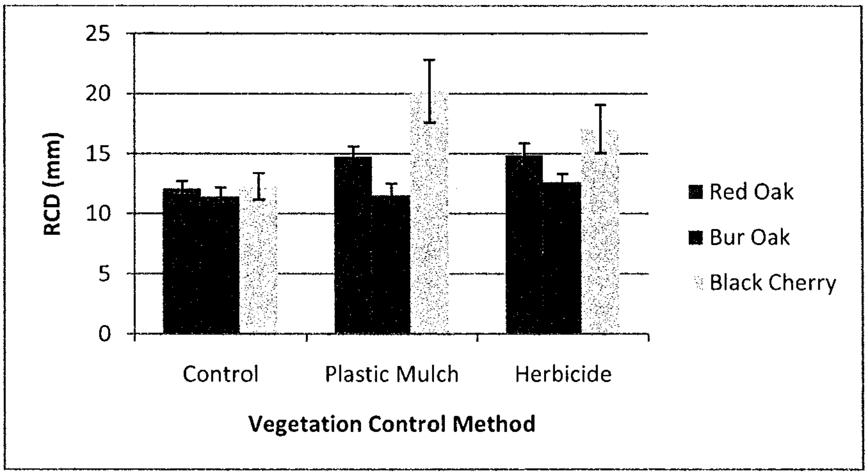


Figure 10. Average root collar diameter for planted seedlings with different vegetation management three years post establishment i) black cherry, ii) bur oak, and iii) red oak. Bars show area within one standard error of the mean.

Biomass accumulation in planted oaks was not affected by the vegetation management (p=0.35), but shoot and total biomass varied significantly between the oak species (p=<0.001) (Table 8). Red oak seedlings were significantly larger than bur oak seedlings in shoot, below ground and total biomass measurements (Figure 11).

Table 8. ANOVA results for biomass accumulation three years post establishment for planted red oak and bur oak seedlings with different vegetation management harvested three years after establishment i) shoot, ii) root and iii) total biomass. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ^{ns} indicate non-significance.

Source	df	Mean Square	F	p-value
i) Above ground biomass				
Species	1	3.261	17.399	<0.001***
Vegetation Management	2	0.199	1.062	0.350^{ns}
Species x Vegetation Management	2	0.061	0.327	0.722ns
Error	94	0.187		
ii) Below ground biomass				
Species	1	0.158	0.889	0.348^{ns}
Vegetation Management	2	0.228	1.288	0.281^{ns}
Species x Vegetation Management	2	0.036	0.202	0.818^{ns}
Error	94	0.177		
iii) Total biomass				
Species	1	0.732	4.291	0.041*
Vegetation Management	2	0.201	1.18	0.312^{ns}
Species x Vegetation Management	2	0.05	0.294	0.746^{ns}
Error	94	0.171		

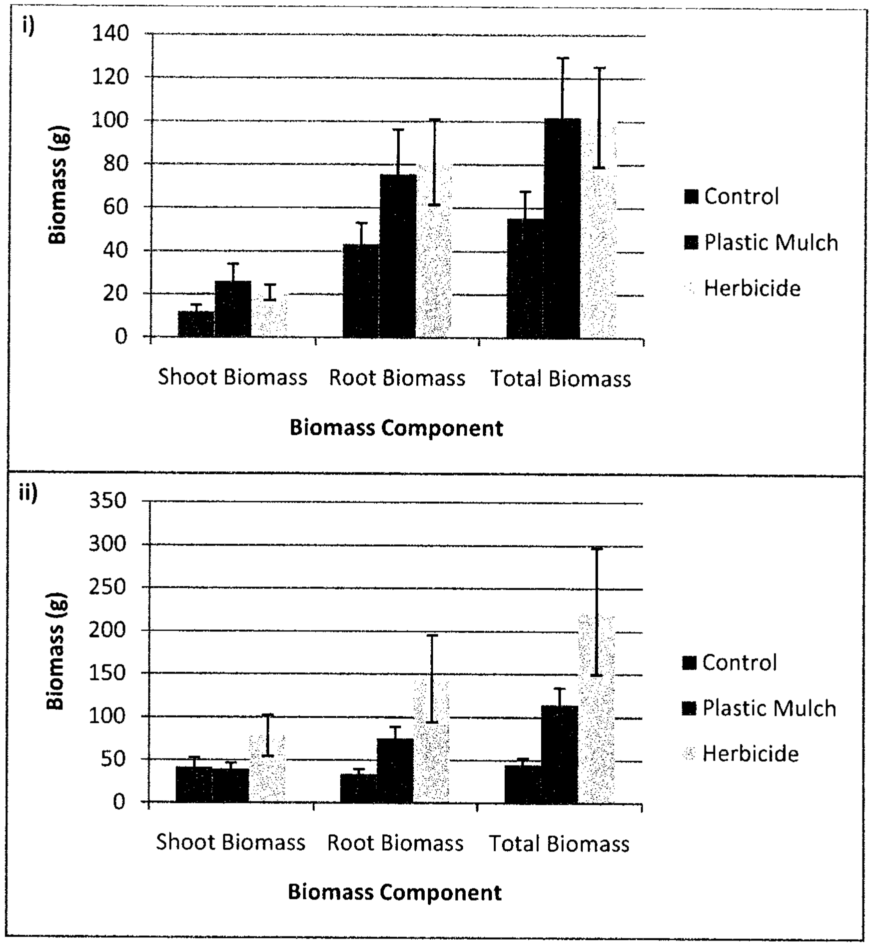


Figure 11. Average shoot, root and total biomass accumulations for planted i) bur oak and ii) red oak seedlings with different vegetation management treatments, harvested three years after establishment. Bars show area within one standard error of the mean.

Directly Seeded Seedlings

Due to poor germination black cherry seedlings were not included in the directly seeded results. The oaks grew at a slow but consistent rate and were most impacted by the vegetation management ($p=<0.001$) (Table 9). Both red oak (Figure 12) and bur oak averaged a total height of approximately 15 cm by the end of the 2008 growing season. Herbicide application positively influenced crop tree growth and was superior to the other two vegetation management treatments. Plastic mulch had a negative impact on directly seeded trees and this trend continued into the third year.

Table 9. ANOVA results for total height growth for directly seeded plots with different vegetation management harvested three years after establishment. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ^{ns} indicate non-significance.

Source	df	Mean Square	F	p-value
Species	1	2.587	0.029	0.866^{ns}
Vegetation Management	2	1796.732	19.931	<0.001***
Species x Vegetation Management	2	291.195	3.23	0.040*
Error	503	90.147		

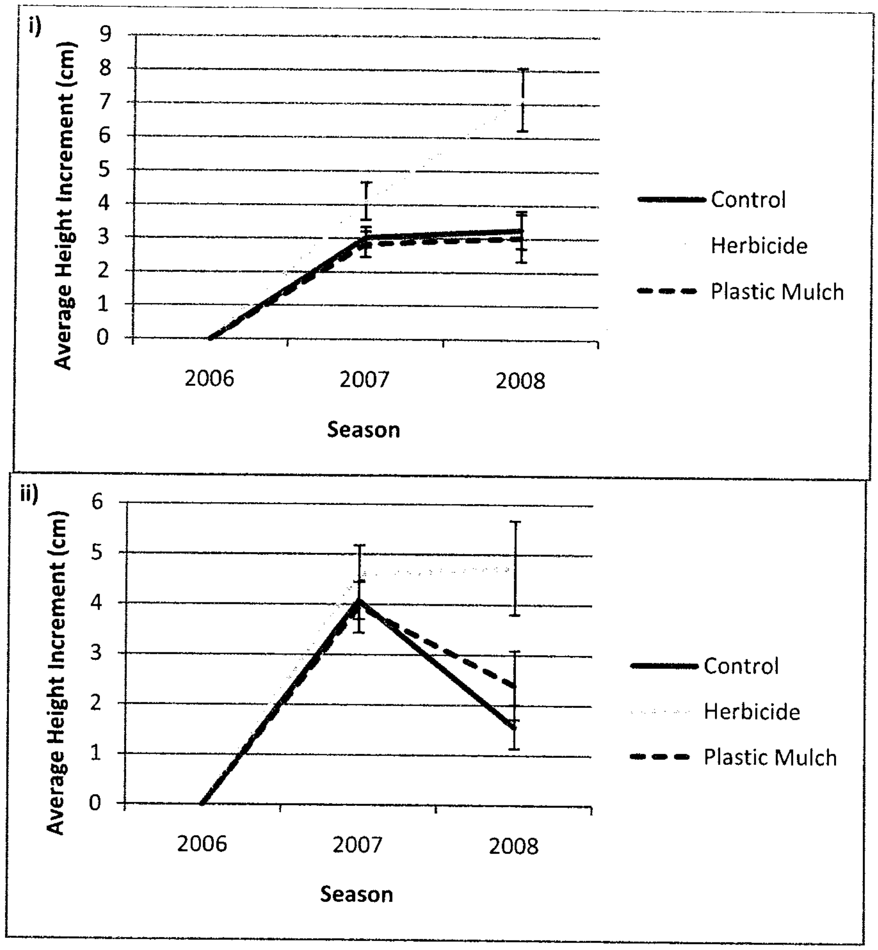


Figure 12. Average total height growth for directly seeded i) bur oak, and ii) red oak seedlings with different vegetation management treatments, harvested three years after establishment. Bars show area within one standard error of the mean.

Annual average height increments for directly seeded plots were not significantly different across species but were significantly different across vegetation management treatments (p=<0.001) (Table 10). A significant decrease in height increment is seen during the 2007 growing season (Figure 13).

Table 10. ANOVA results for average annual height growth for directly seeded plots with different vegetation management harvested three years after establishment. * indicates significance at $\alpha=0.05$, ** indicates significance at $\alpha=0.01$, *** indicates significance at $\alpha=<0.001$ and ns indicate non-significance.

Source	df	Mean Square	F	p-value
Species	1	9.386	0.358	0.550^{ns}
Vegetation Management	2	387.911	14.787	$<0.001^{***}$
Species x Vegetation Management	2	12.123	0.462	0.630^{ns}
Error	545	26.233		

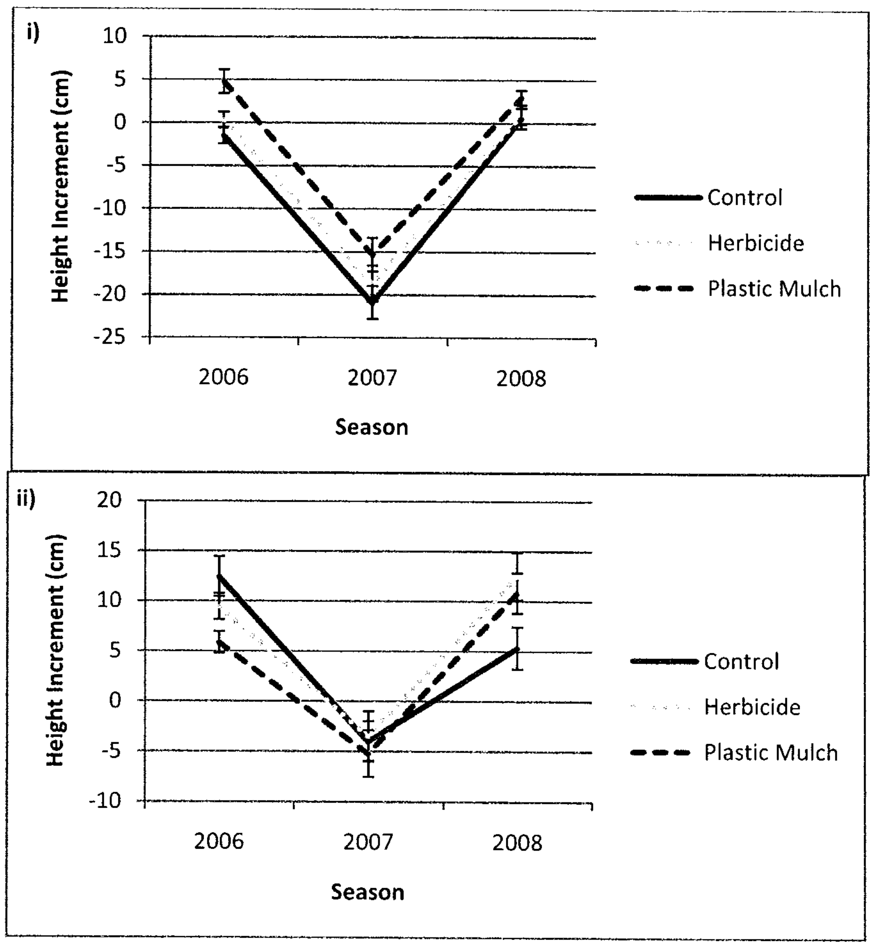


Figure 13. Average annual height increment for directly seeded i) bur oak, and ii) red oak seedlings with different vegetation management treatments, harvested three years after establishment. Bars show area within one standard error of the mean.

Both species and vegetation management type had a significant influence on the root collar diameters of directly seeded oak trees (Table 11). Bur oak (Figure 14) had a significantly higher root collar diameter than red oak. Plastic mulch and herbicide application produced similar results, with herbicide use allowing significantly larger root collars than the control.

Table 11. ANOVA results for directly seeded root collar diameters with different vegetation management harvested three years after establishment. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ^{ns} indicate non-significance.

Source	df	Mean Square	F	p-value
Species	1	0.203	7.222	0.008^{**}
Vegetation Management	2	0.151	5.349	0.005^{**}
Species x Vegetation Management	2	0.024	0.851	0.428^{ns}
Error	212	0.028		

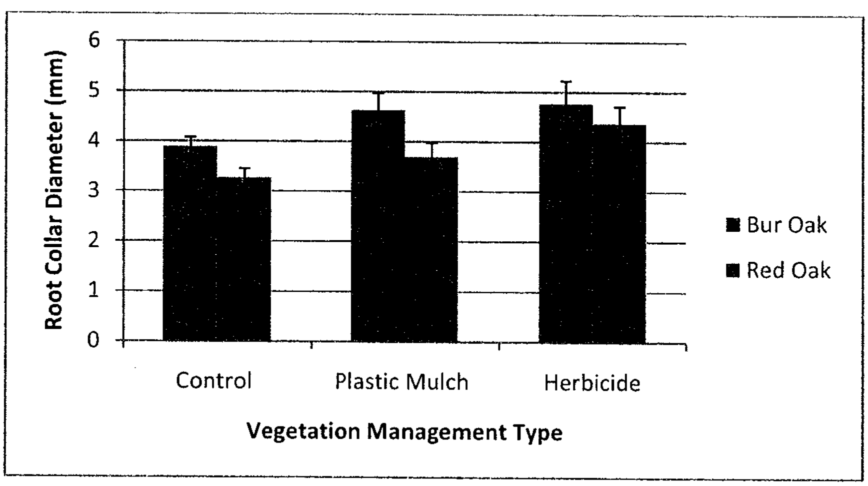


Figure 14. Average root collar diameter for directly seeded seedlings with different vegetation management treatments, harvested three years after establishment. Bars show area within one standard error of the mean.

Biomass components for directly seeded oak seedlings were significantly affected by vegetation management (Table 12). Vegetation control produced significantly greater biomass the control. Both plastic mulch and herbicide application were statistically similar when applied to red oak and yielded approximately 100 g of total biomass per seedling (Figure 15). Bur oak produced less consistent results.

Table 12. Biomass accumulation three years post establishment for directly seeded red oak and bur oak seedlings i) shoot, ii) below ground and iii) total biomass with different vegetation management harvested three years after establishment. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ns indicate non-significance.

Source	df	Mean Square	F	p-value
i) Above ground biomass				
Species	1	0.206	1.158	0.285^{ns}
Vegetation Management	2	0.659	3.699	0.029^{*}
Species x Vegetation Management	2	0.106	0.598	0.552^{ns}
Error	89	0.178		
ii) Below ground biomass				
Species	1	0.002	0.007	0.933^{ns}
Vegetation Management	2	0.683	3.086	0.051^{ns}
Species x Vegetation Management	2	0.188	0.85	0.431ns
Error	89	0.221		
iii) Total biomass				
Species	1	0.003	0.017	0.897^{ns}
Vegetation Management	2	0.739	3.754	0.027^{*}
Species x Vegetation Management	2	0.160	0.814	0.446^{ns}
Error	89	0.197		

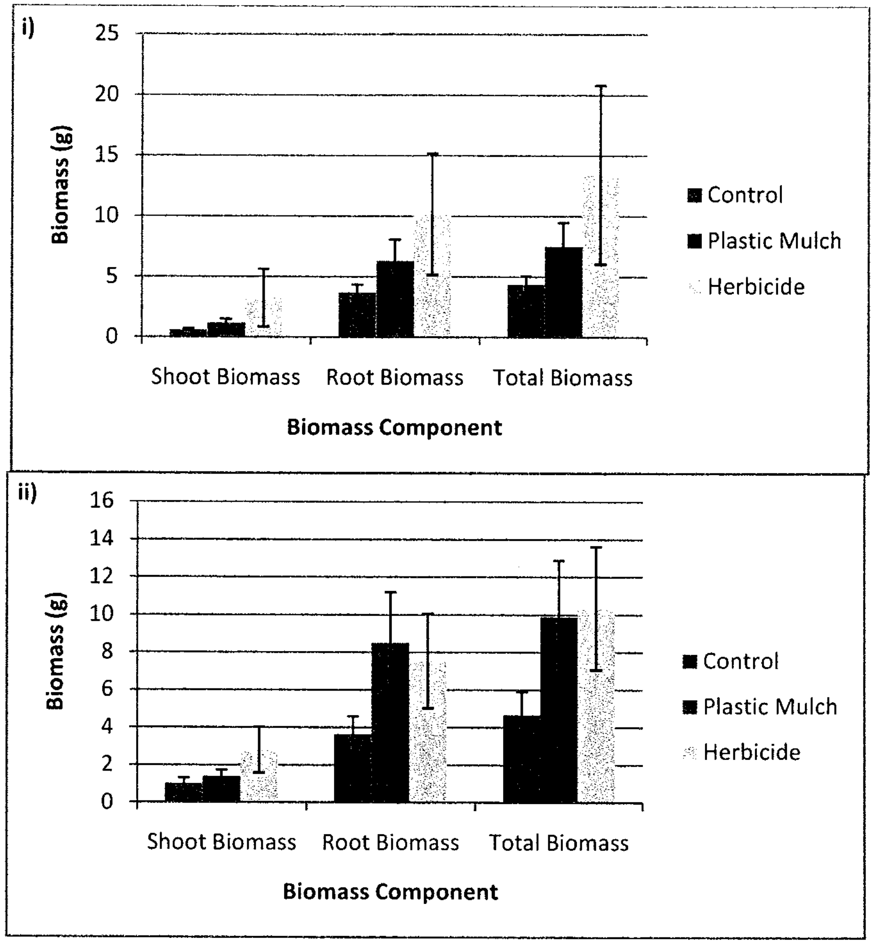


Figure 15. Average shoot, root and total biomass accumulation for directly seeded i) bur oak and ii) red oak seedlings with different vegetation management treatments, harvested three years after establishment. Bars show area within one standard error of the mean.

<u>Root-to-Shoot Ratio</u>

Root-to-shoot ratios were significantly different between the two planting methods and between the two oak species, but did not differ with vegetation management treatment (Table 13). Directly seeded trees had greater root-to-shoot ratios than planted seedlings (Figure 16). In both planting types bur oak had a greater ratio than red oak averaging about 4.50 and 5.75 respectively in seeded plots and 2 and 3.5 in the planted seedling plots.

Table 13. ANOVA results for Root-to-shoot ratios for i) planted and ii) directly seeded oak with different vegetation management harvested three years after establishment. * indicates significance at α=0.05, ** indicates significance at α=0.01, *** indicates significance at α=<0.001 and ns indicate non-significance.

Source	df	Mean Square	F	p-value
i) Planted seedlings				
Species	1	33.582	4.851	0.030*
Vegetation Management	2	3.471	0.501	0.607ns
Species x Vegetation Management	2	4.217	0.609	0.546ns
Error	89	6.923		
ii) Directly seeded seedlings	1	780.186	610.302	<0.001***
Species	1	64.289	50.29	<0.001***
Vegetation Management	2	0.147	0.115	0.891ns
Species x Vegetation Management	2	1.673	1.309	0.275ns
Error	94	1.278		

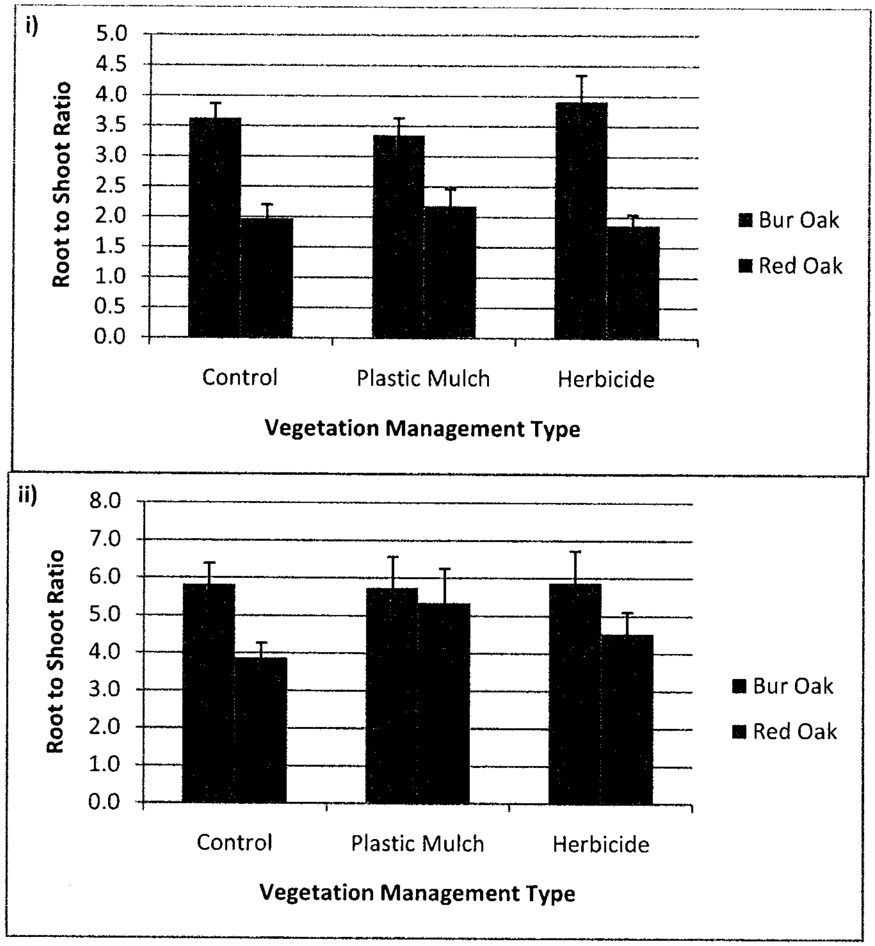


Figure 16. Root-to-shoot ratios of i) planted and ii) directly seeded seedlings with different vegetation management treatments, harvested three years after establishment. Bars show area within one standard error of the mean.

BIOMASS EQUATIONS

Non-linear regression provided the best estimate for biomass accumulation patterns. The power function was most suitable; young tree seedlings reach a threshold where they begin to rapidly accumulate biomass and the power function can relate to this. Biomass estimates derived were both precise and accurate, having high R^2 values and low standard error for each co-efficient (Table 14). R^2 values were similar within species and planting type, but differed between species. Planted bur oak (Figure 17) had more consistent biomass accumulation patterns, which led to a better estimate (R^2=0.875 to 0.879). Planted red oak (Figure 19) had the greatest biomass accumulation but the variability in data led to low R^2 (0.524 to 0.618) values. The directly seeded seedlings had the most stable biomass data and very high R^2 values. Directly seeded bur oak (Figure 18) had R^2 values of 0.958 for root biomass and 0.991 for shoot biomass accumulation, red oak (Figure 20) had an R^2 value of 0.922 for shoot biomass and 0.943 for root biomass and seeded

Table 14. Allometric biomass equations for three year old bur oak and red oak seedlings.

Species	Planting Type	Biomass Component	N	Predictor Variable	a	a Standard Error	b	b Standard Error	Adjusted R2
Or	Planted	Shoot	23	Ht	0.01	0.012	1.938	0.243	0.618
Or	Planted	Root	23	Ht	0.01	0.015	2.073	0.309	0.524
Or	Planted	Total	23	Ht	0.019	0.026	2.024	0.273	0.576
Or	Seeded	Shoot	19	RCD	0.066	0.024	2.064	0.163	0.922
Or	Seeded	Root	19	RCD	0.188	0.070	2.241	0.161	0.943
Or	Seeded	Total	19	RCD	0.252	0.091	2.206	0.158	0.942
Ob	Planted	Shoot	16	RCD	0.002	0.003	3.440	0.419	0.877
Ob	Planted	Root	16	RCD	0.027	0.029	3.024	0.356	0.875
Ob	Planted	Total	16	RCD	0.028	0.030	3.109	0.362	0.879
Ob	Seeded	Shoot	21	RCD	0.006	0.004	3.260	0.235	0.991
Ob	Seeded	Root	21	RCD	0.176	0.080	2.289	0.169	0.958
Ob	Seeded	Total	21	RCD	0.148	0.069	2.491	0.173	0.973

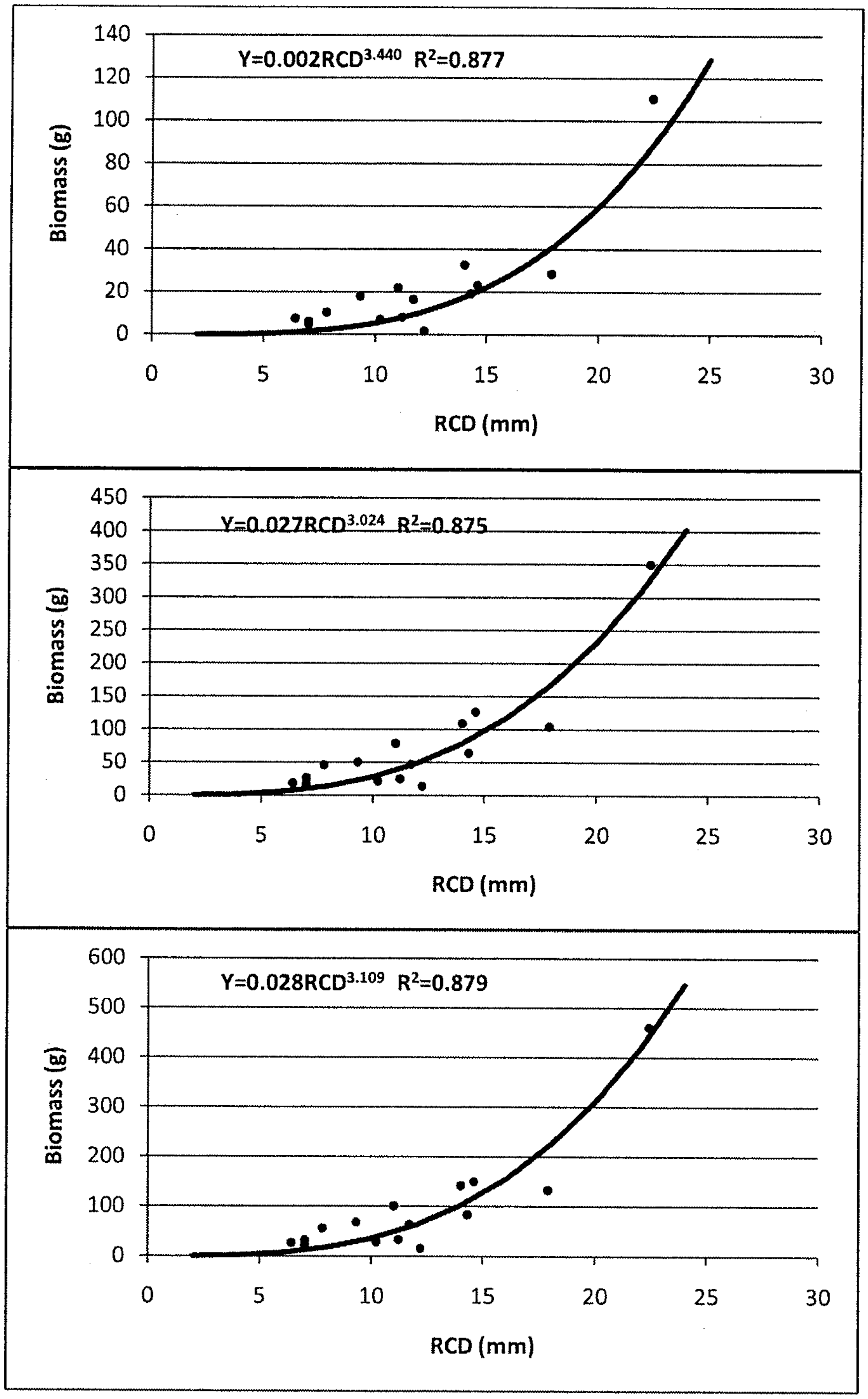


Figure 17. Non-linear regression results for shoot (top) root (middle) and total (bottom) biomass accumulation of planted bur oak seedlings harvested three years post establishment.

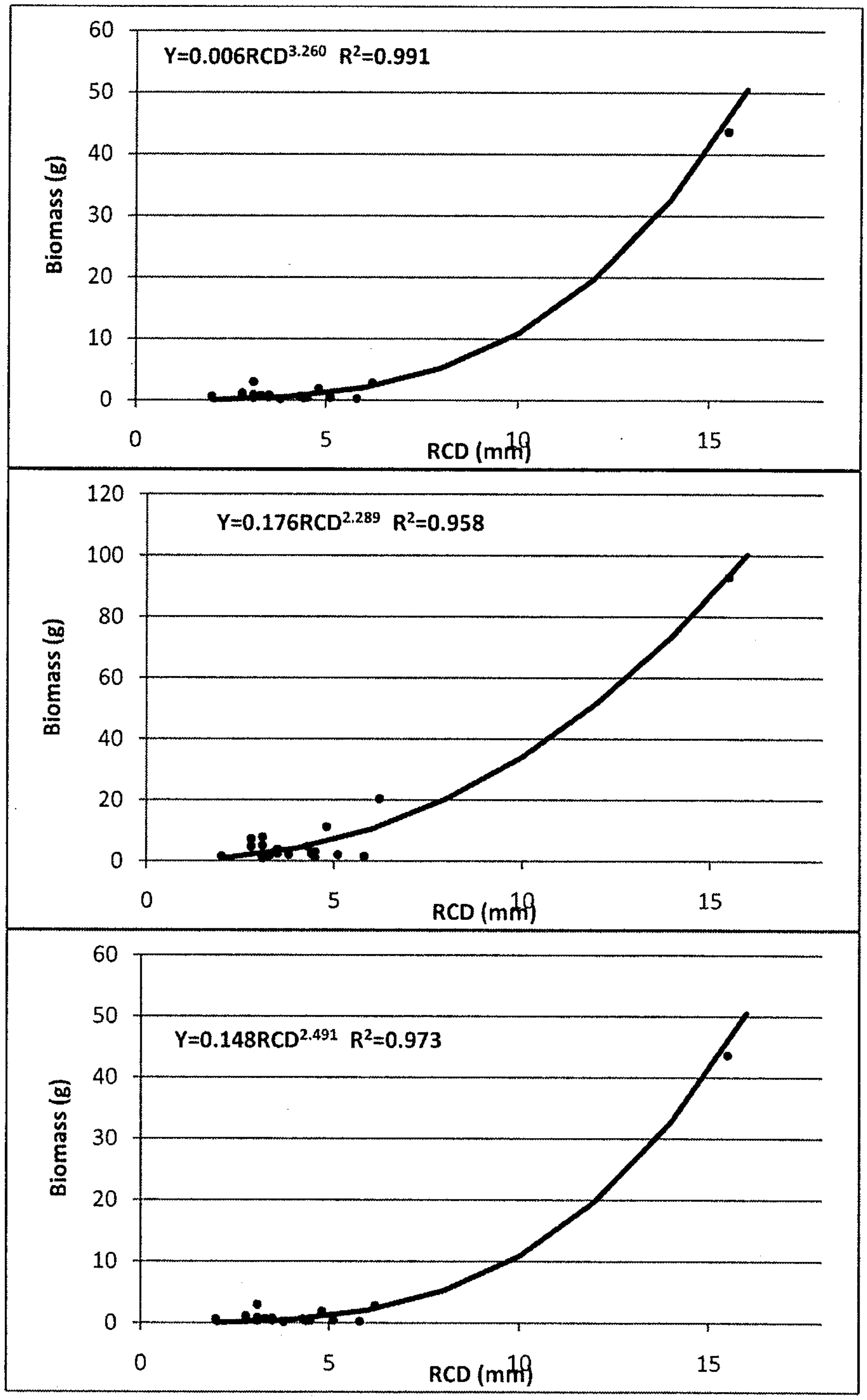


Figure 18. Non-linear regression results for shoot (top) root (middle) and total (bottom) biomass accumulation of directly seeded bur oak seedlings harvested three years post establishment.

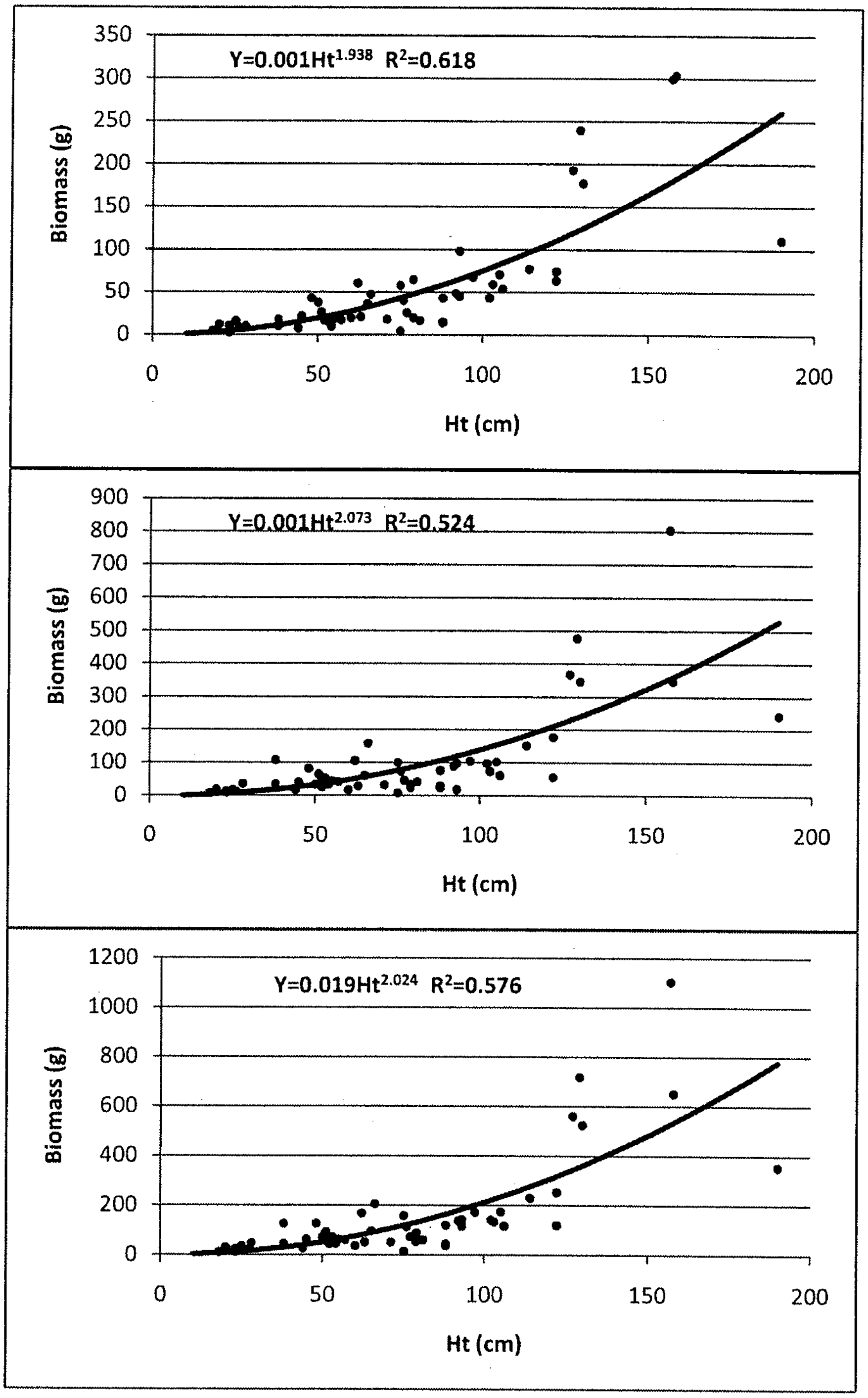


Figure 19. Non-linear regression results for shoot (top) root (middle) and total (bottom) biomass accumulation of planted red oak seedlings harvested three years post establishment.

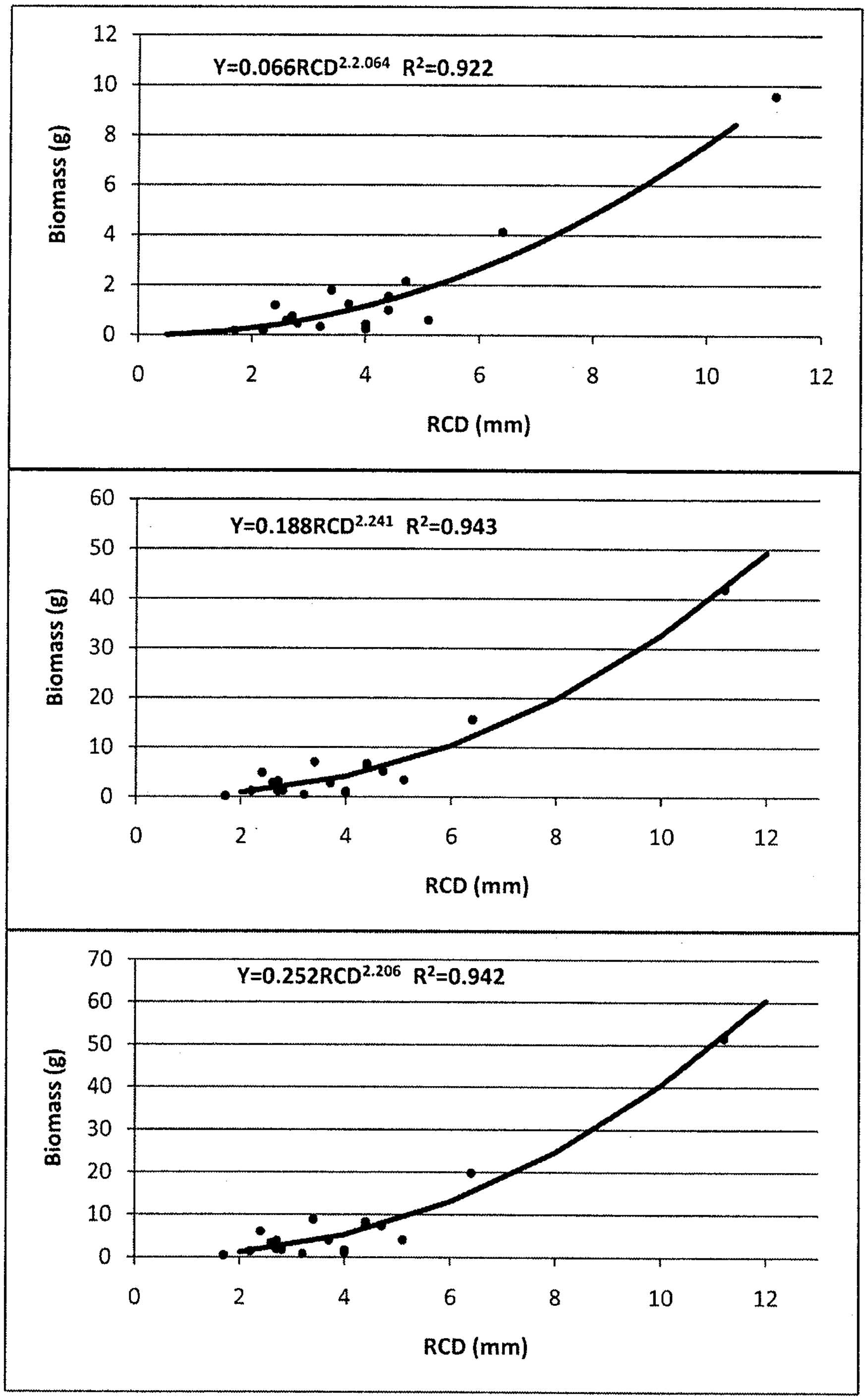


Figure 20. Non-linear regression results for shoot (top) root (middle) and total (bottom) biomass accumulation of directly seeded red oak seedlings harvested three years post establishment.

MODEL COMPARISONS

Regression models were compared using an F-test to determine if a single model could be used to describe the biomass accumulation. Models were tested between species and within species and models and resulted in three comparable equations (Table 15). Shoot biomass in planted red oak seedlings can be accurately predicted using the total biomass estimates for planted red oak seedlings. In addition, total biomass estimation for both red oak and bur oak seedlings can be used interchangeably.

Table 15. Non-linear regression model F-test (α=0.05) comparisons for planted and directly seeded oak seedlings within species and between species.

Original Model	Comparison Model	F-Stat	DF	Critical Value	Results
ObP TB	ObP SB	2.40	15/15	213.87	Significant
ObP TB	ObP RB	2.40	15/15	8.50	Significant
OrP TB	OrP SB	1.57	54/54	-0.40	Insignificant
OrP TB	OrP RB	1.57	54/54	-42.14	Significant
ObS TB	ObS SB	2.17	19/19	629.99	Significant
ObS TB	ObS RB	2.17	19/19	6.36	Significant
OrS TB	OrS SB	2.22	18/18	324.54	Significant
OrS TB	OrS RB	2.22	18/18	9.21	Significant
ObP TB	OrP TB	1.86	15/54	0.10	Insignificant
OrP TB	ObP TB	2.17	54/15	1.14	Insignificant
ObS TB	OrS TB	2.20	19/18	34.35	Significant
OrS TB	ObS TB	2.18	18/19	12.56	Significant

SUMMARY TOOL

The summary tool (Table 16) scales up the single-tree metrics into a hypothetical one hectare plantation. This type of information can help landowners understand the short-term impacts of their initial management decisions on the cost to establish a plantation and the benefit seen as a result. The tool output shows that planted red oak treated with an annual herbicide application costs $840 greater than the cheapest treatment combination but the strong three-year growth measurement create the least cost per kg of biomass accumulated ($36/kg). There are four comparable treatments identified by the summary tool: planted bur oak with plastic mulch, directly seeded bur oak with herbicide, planted red oak with the control and directly seeded red oak with herbicide yield similar biomass accumulations and cost per kilogram of biomass.

Table 16. Summary tool used to scale up single tree metrics to a hectare level.

Species	Planting Method	Vegetation Treatment	Initial Planting Density	Three year Survival	Average Ht (cm)	Average RCD (mm)	Total trees/ha	Biomass (kg)	Establishment Costs ($)	Cost/Kg Biomass
Ob	Planted	Control	1500	34%	44.7	11.4	510	4.41	6,260	1,420
Ob	Planted	Plastic Mulch	1500	56%	49.6	11.54	840	36.96	6,665	180
Ob	Planted	Herbicide	1500	44%	48.5	12.6	660	48.73	6,440	132
Ob	Seeded	Control	7500	86%	15.6	3.9	6450	3.27	5,428	1,660
Ob	Seeded	Plastic Mulch	7500	50%	13.1	4.6	3750	21.71	5,833	269
Ob	Seeded	Herbicide	7500	77%	21	4.7	5775	40.37	5,608	139
Or	Planted	Control	1500	87%	65.9	12.11	1305	43.71	6,260	143
Or	Planted	Plastic Mulch	1500	90%	77.6	14.75	1350	111.69	6,665	60
Or	Planted	Herbicide	1500	85%	81.9	14.89	1275	180.61	6,440	36
Or	Seeded	Control	7500	89%	13.4	3.2	6675	4.86	5,600	1,152
Or	Seeded	Plastic Mulch	7500	68%	15	3.7	5100	17.99	6,005	334
Or	Seeded	Herbicide	7500	86%	18.5	4.4	6450	42.70	5,780	135

DISCUSSION

PLANTING METHOD

Planting method was included in the treatment structure for this study to shed light on the ability of directly seeded hardwoods to produce comparable results to planted hardwoods. Directly seeded seedlings have inferior production compared to planted seedlings in the short term, consistent with other published work (Twedt and Wilson 2002, Löf *et al*. 2004). Total height, average annual height increment, root collar diameter and biomass production for seedlings in this study were all significantly less for directly seeded seedlings compared to planted nursery stock.

Height increment is sensitive to browsing and other unpredictable events that result in negative annual height growth. During the 2007 season there was an obvious decrease in height increment that mostly affected the oak species. This large decrease in annual increment did not affect the total height accumulation nor did it affect the survival of the planted seedlings. The decrease suggests that between the fall of 2006 and the fall of 2007 there was a significant event that influenced the overall production of the plantation. A harsh winter with a low snow accumulation could have led to increased animal browsing in the plots. Similar adverse effects were not seen in the directly seeded plots because seedlings were small enough to be protected from the winter by the snow pack.

Root-to-shoot ratio was the only response variable for which produced greater results for directly seeded seedlings. This is a result of a concentration of annual growth in root production (Dey *et al.* 2008). Due to their slow growing nature and susceptibility to die back and predation, substantial root mass is required to sustain and support growth throughout juvenile development.

TREE SPECIES

The role of tree species in this study was to assess the suitability of bur oak, red oak and black cherry to an afforested environment. The 2+0 planting stock gave red oak a competitive advantage over the 1+0 bur oak and black cherry planted stock. The differences in stock quality can have a substantial impact on the short-term growth and development of seedlings and this can explain the superior growth see in the planted red oak seedlings. Red oak produced the most consistent seedling germination, survival and growth and its success reinforces other published studies on afforestation (von Althen 1991, Pedlar *et al.* 2007 and Dey *et al.* 2008). From seed, red oak produced consistent germination and grew fast making it a reliable crop tree choice when direct seeding. Similarly, as a planted seedling, red oak had good survival and good production. Red oak is a versatile species that can persist on a wide variety of sites and can stay healthy in a competitive environment by slowly building root mass to the point where it can eventually surpass weed growth (Dey *et al.* 2008).

Black cherry's unreliable germination makes it a risky crop tree for direct seeding. However, planted black cherry excelled compared to the oaks. As a pioneer species black cherry was able to make efficient use of the available resources and accumulate a significant amount of biomass. On an appropriate site black cherry will outperform oaks in early plantation development and has the potential to grow rapidly during a cool moist summer (Marquis 1991). During the growing season after the unfavourable winter conditions of 2007-2008, black cherry continued to produce positive height increments.

For all three years bur oak had inferior growth properties to red oak. However, directly seeded bur oak trees accumulated greater total biomass with small standard errors within treatments. This deviation can be attributed to the significantly greater root biomass produced by bur oak. Bur oak develops a large taproot that enables it to be drought resistant (Cogliastro *et al.* 2003) and this coupled with its poor above ground growth led to a high root-to-shoot ratio. Large root biomass allows seedlings to store carbohydrates and actively absorb water nutrients and support shoot growth even in resource limiting situations (Knapp *et al.* 2006). Root-to-shoot ratios vary with each species and with tree age (Gerhardt and Fredricksson 1995). Generally, oak seedlings have a high root-to-shoot ratio (Knapp *et al.* 2006) and open grown seedlings favour root growth over shoot growth (Kolb and Steiner 1990, Gardiner and Hodges 1998). Root growth is also favoured when soil moisture and nutrient availability is low (Vitousek and Sanford 1986, Cairns *et al* 1997). The ratios in this study can be viewed as an underestimate, because our root extraction methods only enabled us to harvest coarse roots, leaving biomass on site in the form of fine roots. All root-to-shoot ratios in this study were greater than 1 (1.8 to 5.8), indicating that below ground growth is considerably larger than above ground growth. These values are comparable to the root-to-shoot ratios observed in young directly seeded holm oak (*Quercus ilex* L.) forests where seedlings not treated with vegetation control had an average ratio of 3.22 and when site preparation was conducted a ratio of 2.09 (Navarro *et al.* 2006). Directly seeded trees have the highest ratios in the study. The seeded trees had very small height measurements and their root masses were over three times that of the shoot portion of the tree. The high root-to-shoot ratios in this study can be attributed to oaks natural growth patterns and the annual reductions in height growth caused by resource competition and seedling predation.

VEGETATION MANAGEMENT

Vegetation management is an investment was used to improve the growth of crop trees. Löf and Welander (2004) found that vegetation management did not have a significant effect on tree growth until the second season. In this study site preparation allowed adequate weed control in the first year. During the second and third growing season the mulching and herbicide applications were both improvements over no management. Herbicide application was the superior technique for controlling competing vegetation and improving crop tree growth. Plastic mulch produced statistically similar results to the herbicide application, but its success was less consistent and produced lower averages than the herbicide treatment. Plastic mulch can act as a visual cue to herbivores and can provide small mammal habitat, which may make seedlings more susceptible to predation (Dey *et al.* 2008). In addition, a small amount of weeds are allowed to grow through the center hole in the plastic mulch and may influence a seedling's capacity to absorb light.

The only situation where vegetation management did not improve the performance of the crop trees was in the seed germination. Plastic mulch and herbicide produced no significant gains in germination rates and thus proved to be unneeded at that point in plantation development. Plastic mulch, due to its ability to modify soil environments within the micro site (Dey and Buchanan 1995) may have created an inhospitable germination environment for acorns which are sensitive to soil moisture and temperature. If the mulch was incorrectly applied over the seeds, the opening for the seedlings to emerge may have been in the wrong location and would have provided no light for growth.

BIOMASS EQUATIONS

Biomass estimates for young, artificially regenerated plantations on agricultural land are rare if not non-existent therefore, the results presented in this paper are difficult to put into perspective. In addition, the decisions to aggregat all vegetation management treatments into one dataset, the small sample size and the root excavation technique make inference difficult. On the other hand, the biomass equations developed in this paper had high degrees of variance explained and low standard errors which suggest that predictions using these equations will be precise.

Biomass estimates were for the most part unique; however, the planted oak seedlings had similar equations. From the growth data it is evident that the red oak seedlings had a higher average diameter, and biomass accumulation after three years, yet its biomass predictions are similar to those for bur oak. This may be due to the large variability in growth measures within species. Total biomass estimates for red oak also produced similar predictions to shoot biomass estimates for the same species; intuitively this does not make sense. Root biomass accumulation draws most of the resources when the plant is under stress and varies very little as a result of environmental stress when compared to shoot accumulation. Therefore, one would expect that a measure of shoot biomass would not be driving the total biomass measurements. Dramatic fluctuations in stem height as a result of seedling predation and other environmental stressors could have resulted in similar biomass curves in both cases.

CONCLUSIONS

Using the results created by the summary tool a landowner can assess the achievement of his/her management objectives. In this study the objectives were to assess direct seeding as an alternative planting technique to planting seedlings, assess plastic mulch as a comparable vegetation management alternative to herbicide and to assess the growth and development of bur oak, red oak and black cherry three years after planting. The statistical analysis presented makes clear conclusions about the effectiveness of each treatment studied, but the real life product of each treatment combination is difficult to visualize. When the information presented in this study is scaled up to a plantation level, the impacts of the decisions made pre-establishment become clear.

After three years it is evident that direct seeding cannot produce comparable results to planted seedlings. Directly seeded plots have a comparable survival percentage after three years and because initial densities were high, some seeded treatments produced similar results to planted seedlings. In particular the directly seeded plots treated with an annual herbicide application have about 5 times the number of stems compared to the planted control plots and a result their total biomass accumulations per hectare are close. Without the high initial density, biomass per hectare would not be comparable. The lack of production compared to planted seedlings may be warranted given the costs saving when using direct seeding. As with other studies direct seeding in this study costs between 50% and 67% less than establishing a plantation from nursery stock (Dey *et al.* 2008). However, when herbivore protection and site preparation is considered total savings are closer to 10-20%. Therefore, as the plantation struggles to achieve dominance over weedy competition, continued financial investments will be required for at least 7 years making direct seedling less and less cost effective.

The summary tool also highlights the benefits of vegetation management. Biomass accumulation per hectare, which is a relationship between growth patterns and stem densities, is substantially greater for seedlings treated with either plastic mulch or herbicide. Annual herbicide produced the greatest total biomass per hectare and this reflects its statistical significance. Plastic mulch, although not as effective as an annual herbicide application, does improve seedling growth and survival and has proved to be an effective vegetation management alternative.

Black cherry is not well suited to direct seeding because of its poor germination but its growth as a transplant was greater than oak growth. Black cherry was not included in the summary tool because it was not included in the biomass analysis, but its survival and growth data suggest biomass per hectare results would be greater than the best red oak values. Bur oak produced inferior results to red oak in both directly seeded plantations and plantations derived from transplants. The average survival, germination, growth measurements and biomass production for bur oak were all less than red oak. Due to its superior growth properties as a transplant and from seed, red oak is the most suitable species studied for afforestation.

The short-term results reviewed in this thesis demonstrate the common challenges faced in afforestation projects in southern Ontario. Intense weed and herbivore competition created a stressful growing for the tree seedlings that lead to varying levels of production. Applying vegetation management to planted nursery stock yielded the most consistent and productive seedling growth in the short-term where as directly seeded seedlings grew very little. Future monitoring and assessment of the plantations will further investigate the influence of planting method and vegetation management on the growth of the crop trees. The 10 year results will be analysed to provide better insight into the success or failure of the direct seeding treatment and provide a definitive answer to whether or not direct seeding can be used as a reliable regeneration method on marginal agricultural land in southern Ontario.

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APPENDIX

APPENDIX I
SOIL ANALYSIS

Soil at the Pittock is a consistent silty sand comprised of 65% sand, 30% silt and 5% clay. Soil nutrient composition varies among study plots, depending on slope position with the lower slope position containing less Ca, K and Mg, but more P than elevated soil plots. Soil at the Fingal site is a silty loam with 30% sand, 50% silt and 20% clay. The soil has high calcium content and nutrient distribution is consistent at all soil plots. Soil at the Littlejohn site is a silty loam containing 35% sand, 55% silt and 15% clay. Soil nutrients are distributed evenly across the site and are rich in sodium. A complete soil analysis for all three sites is presented in Table A1.

Table A1. Soil chemical properties by site and slope position.

Site	Slope Location	Ca (mg/kg)	K (mg/kg)	Mg (mg/kg)	Na (mg/kg)
Fingal	lower	4470	94.7	163.6	10.25
Fingal	mid	4463.7	81.7	155.7	9.9
Fingal	upper	2734.7	127	173.3	5.87
Littlejohn	lower	1888.7	87.4	215.2	5.41
Littlejohn	mid	2100.3	67.2	118.3	7.68
Littlejohn	upper	943	49.6	134	9.7
Pittock	lower	515.7	152.9	55.5	-
Pittock	mid	1404.2	79.5	212.7	4.05
Pittock	upper	1412.4	64.2	187.9	6.35

APPENDIX II
ORIGINAL ROOT COLLAR DIAMETER MEASUREMENTS

Table A2. 2008 average RCD by planting method, species and vegetation managment type

Planting Method	Tree Species	Vegetation Management	RCD
Planting	Black Cherry	Control	12.3
Planting	Black Cherry	Plastic Mulch	13.7
Planting	Black Cherry	Herbicide	8.9
Planting	Bur Oak	Control	11.2
Planting	Bur Oak	Plastic Mulch	8.8
Planting	Bur Oak	Herbicide	12.7
Planting	Red Oak	Control	10.3
Planting	Red Oak	Plastic Mulch	12.3
Planting	Red Oak	Herbicide	11.8
Seeding	Black Cherry	Control	4.1
Seeding	Black Cherry	Plastic Mulch	2.7
Seeding	Black Cherry	Herbicide	5.1
Seeding	Bur Oak	Control	3.0
Seeding	Bur Oak	Plastic Mulch	4.6
Seeding	Bur Oak	Herbicide	4.0
Seeding	Red Oak	Control	2.8
Seeding	Red Oak	Plastic Mulch	3.7
Seeding	Red Oak	Herbicide	3.6