EVALUATING SHORT ROTATION POPLAR BIOMASS ON AN EXPERIMENTAL LAND-FILL CAP NEAR ANCHORAGE, ALASKA

By

Amanda G. Byrd

Recommended:

Advisory Committee Chair

Chair, Civil and Environmental Engineering

Approved:

Dean, College of Engineering and Mines

Dean of the Graduate School

29 August 2013

Date

EVALUATING SHORT ROTATION POPLAR BIOMASS ON AN EXPERIMENTAL LAND-FILL CAP NEAR ANCHORAGE, ALASKA

A THESIS

Presented to the Faculty
of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

By
Amanda G. Byrd

Fairbanks, Alaska

May 2013

Abstract

Biomass energy has enjoyed a resurgence of scientific interest recently. Indeed, biomass may have the potential to replace diesel fuel as the primary source of heating in some parts of Alaska. In addition to forest biomass, short rotation crops have been considered as a sustainable source of woody biomass, and a potential sink for carbon sequestration. In this study, *Populus balsamifera* was evaluated as a short rotation crop for use as an energy source in Southcentral Alaska. Growth and yield rates were measured on an established *P. balsamifera* stand under a two-year rotation, yielding an annual biomass production of 5,530 kg/ha/yr. A fertilizer application study was conducted and demonstrated no effect on growth. Energy content of *P. balsamifera* measured 19,684 kJ/Kg, with a total energy yield of 217,715 MJ/ha after two years. Carbon sequestered below ground was estimated at least 5,338 kg/ha. Biomass may not be carbon neutral, but the carbon emitted from burning biomass is at least partially renewable. With use in high-efficiency boilers, there is potential for biomass to offset costs, and even save money by displacing diesel heating fuel.

Dedication Page

This thesis is dedicated to my mum, Betty Byrd, who has always encouraged me to be my very best.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I would like to express my deepest appreciation to my committee chair Dr William Schnabel for his enthusiasm, advice, and direction during my project and thesis. He continually offered enthusiastic praise, support, and encouragement, and his interest in the topic was greatly appreciated.

In addition, I would like to thank Dr Stephen Sparrow for his great depth of knowledge in this topic. I am very grateful for the time that he afforded me during my project, and his candor. I would like to thank Gwen Holdmann who is an incredibly inspiring leader who dreams big, and makes things happen, and Dr David Barnes for his support and encouragement in completing this thesis.

I would like to thank Darleen Masiak for her assistance, advice, editing, and hard work in helping me complete this project. Without her knowledge, great humour, and dedication to great research, I know this project would have been more difficult.

I would like to thank the United States Air Force for funding this project, and Joint Base Elmendorf Richardson for access to the study site and use of their facilities. Also, a big thanks to all of my field technicians and laboratory managers for their important assistance.

I would also like to thank my family and friends for their support and encouragement throughout this degree, especially Melissa and Sara for helping at home when I was out doing field work. And, I would like to thank my 18 beautiful sled dogs who understood when their person needed to focus on studies.

Chapter 1 - Introduction and Objectives

Due to the rising cost of fossil fuels, the lack of long-term price certainty, and the desire to reduce the amount of money leaving the local economy, communities across Alaska are seeking locally available alternative energy sources to provide heat and electricity. This rising cost has become noticeable in remote areas, especially rural communities not connected to the road system (Alaska Energy Authority, 2010). The escalating transportation costs of fuel to these remote communities, in combination with the cost of the fuel itself, have caused some communities to look for alternative means of community heating (Alaska Department Of Commerce Community and Economic Development, 2012). A community's location and its proximity to various natural resources will ultimately determine the types of alternative energy resources available to them. Communities with a local and sustainable wood source could use wood as their main heating fuel. While standing forest biomass has been extensively studied in Alaska, yields of woody species grown as a short rotation coppice crop in Alaska have not been well studied (Garber-Slaght et al., 2009). The information required includes growth rates of the woody species, optimum harvesting frequencies under short rotation coppice (SRC), and a determination regarding the feasibility of SRC biomass as a viable energy resource across the state.

Many communities in Alaska are positioned on large rivers and some of those, especially in Central and Southcentral Alaska, have abundant forest resources. Black and white spruce make up approximately 42% percentage of the forest inventory (Hanson, 2010), while 58% is made up of deciduous species such as paper birch, quaking aspen, balsam poplar, and willow. Some of these hardwoods, especially willow and poplar, could play an important role as short rotation coppice crops in rural Alaska. However, there is little information on the growth rates of these species under short rotation coppicing in Alaska.

Objectives

This thesis evaluates the use of *Populus balsamifera L* as a short rotation energy crop in Southcentral Alaska.

The objective of this study was to evaluate woody SRC crops as a potential heating source in Alaska. More precisely,

1. **Measure the growth rates of *P. balsamifera* under a short rotation harvest and nitrogen fertilizer application.**

Following the harvest of the aboveground biomass in a seven year-old plantation of *P. balsamifera* on an experimental landfill cap in Southcentral Alaska, new biomass production was measured. The annual growth rates of the *P. balsamifera* were measured under a two year short rotation and the effects of fertilization application were assessed.

The following hypotheses were tested:

H_{O1}: The energy and carbon content of the second rotation regrowth will be the same as the energy and carbon content of the initial aboveground biomass.

H_{O2}: After the initial harvest, the nitrogen fertilizer application will have no effect on the biomass regrowth.

2. **Measure the aboveground biomass and develop allometric equations specific to *P. balsamifera* in Southcentral Alaska**

Using diameter at breast height (DBH) and diameter at 30cm (D30), and the dry weight of harvested aboveground biomass, allometric equations were developed for *P. balsamifera* in Southcentral Alaska.

Chapter 2 - Background

2.1 Biomass Utilization in Alaska

Biomass is enjoying a resurgence as a major source of space heating in Alaska. Biomass provides potential opportunities to reduce the cost of heating energy and electricity, as well as the potential ability to reduce carbon emissions. Small, rural communities that depend on diesel can pay up to $10 per gallon for heating and transportation fuel, while larger cities such as Fairbanks pay up to $4.75 per gallon (Alaska Department Of Commerce Community and Economic Development, 2012). The conversion to a local source of biomass energy as a fuel could benefit communities by creating jobs, and by creating a locally sustainable fuel source.

Several Alaskan communities have recently moved to biomass as their primary source of heat for a number of main buildings, housing and schools in their communities. The village of Tanana (population 231), located on the confluence of the Tanana and Yukon Rivers, is one such community that has changed its primary heating source to locally collected biomass. Nine Garn® boilers, cord wood gasification systems, have been installed in the village’s washeteria, city offices, senior citizen center, teacher housing and community center. A recent study (Ketzler, 2012) found that these boilers have reduced heating bills by up to 30%, and saved the community tens of thousands of dollars per year. The eighty cords of wood burned annually offsets 9,800 gallons of heating fuel per year. In addition, this move to biomass energy has created employment for local residents who harvest, cut and deliver the wood for $250 a cord (Ketzler, 2012). A large portion of the wood used in the Tanana boilers has been collected as driftwood originating from upriver bank erosion. As an estimated 300,000 cords of wood are transported by the Yukon and Tanana Rivers annually (Ott et al., 2011), driftwood appears to be a sustainable source of fuel for communities located on these rivers. Another Interior community, Tok (population 1,250), has created fire breaks in their black spruce forest and used that harvested wood to heat the Tok School. While Tok does not have the driftwood supply enjoyed by Tanana, Tok's road access allows for harvest, transportation, and use of the abundant supply provided by the area fire mitigation activities. Three communities on Prince of Wales Island; Craig, Coffman Cove, and Thorne Bay have also used abundant local biomass and employed biomass fired boilers as their primary heat for their schools. Other communities including Juneau and Ketchikan have employed the use of biomass, in the form of compressed wood pellets and wood chips, as a major source of heating for large buildings.

2.2 Poplar as a Woody Biomass Species

Poplar (*Populus sp*.), a fast growing hardwood tree is frequently grown as an energy crop (Rogers et al., 2012, Felix et al., 2008, Guillemette and DesRochers, 2008, Swamy et al., 2006). Poplars are one of the fastest growing genera in temperate climates (Felix et al., 2008). Their high rate of growth contributes to their wide use as wood energy products such as raw material for woodchips (Isebrands and Karnosky, 2001). Trees such as poplar and willow can be cultivated from cuttings taken from one tree to produce clones in a nursery (Rytter, 2006, Das and Chaturvedi, 2009, Swamy et al., 2006, Guillemette and DesRochers, 2008, Kopp et al., 1997b). Alternatively, cuttings of trees can be obtained from wild stock (Schnabel et al., 2012), however most of the research focusing on biomass growth has used nursery-raised clones of proven fast-growing hybrids including *P. trichocarpa* Torr.& A. Gray x *P. deltoides* W. Bartr. ex Marsh*.,* and *P. balsamifera* L. hybrids (Table 1).

Short rotation often implies a harvest schedule of 3-5 years for willow, and 5-7 years for poplar, however rotations of up to 20 years are not uncommon (Rytter, 2012). Moreover, harvest of a single stand can be achieved multiple times by coppicing (Volk et al., 2006, Felix et al., 2008) before replanting is necessary. The growth rates and harvest potential of poplars as a short rotation coppice crop have not yet been fully studied in Alaska, and understanding these factors is necessary to evaluate the feasibility of it as a

Table 1 Aboveground biomass production by poplar trees worldwide. Table adapted from Johansson and Karacic (2011).

Species	Stand age (years)	Tree weight Kg (dia., mm)	Total Production (ton/ha)	Growth Rate (ton/ha/yr)	Trees/ha	Location	References
P. trichocarpa clone Muhle Larsen	5	nr	62	12.4	nr	Germany	(Hofmann-Schielle et al., 1999)
P trichocarpa x *P. deltoides* "Boelare"	4	nr	54.4	13.6	nr	England	(Armstrong et al., 1999)
P trichocarpa x *P. deltoides* Clone 11-11	7	13.4 (77)	127.7	18.2	9530	Washington, USA	(DeBell et al., 1996)
P.x Canadensis "Gelrica"	24	198 (253)	154.8	6.4	782	Sweden	(Persson, 1973)
P. trichocarpa x *P. deltoides* "Beaupré"	6	9.7	45.9	7.7	4732	Sweden	(Telenius, 1999)
P. trichocarpa	12	(151)	55.2	4.6	nr	Norway	(Langhammer and Rep, 1967)
P. deltoides, Clone I-69	6	70.6 (150)	78.4	13.1	1105	China	(Fang et al., 1999)
Unknown Origin	4	(58)	45.2	11.3	nr	Kentucky,USA	(Wittmer and Immel, 1976)
P. deltoides, P. trichocarpa clone 11-11	4	(97)	140.8	35.2	nr	Washington, USA	(Scaracia-Mugnozza et al., 1997)
P. maximowiczii x *P. trichocarpa*	10	13.4 (117)	32	3.2	2388	Maine, USA	(Czapowskyj and Safford, 1993)
P. trichocarpa x *P. deltoides* "Siouxland"	7	46.9 (140)	nr	nr	nr	N. Dakota, USA	(Tuskan and Rensema, 1992)
P. deltoides	11	167.6 (230)	81.6	7.4	487	Mississippi, USA	(Blackmon et al., 1979)
P. trichocarpa x *P. deltoides*	12	146.9	163.2	13.6	1110	B.C. Canada	(Zabek and Prescott, 2006)
P. maximowiczii x *P. trichocarpa*	4	(34)	26.1	6.5	nr	Pennsylvania, USA	(Bowersox and Ward, 1976)
P. trichocarpa	8	(46)	60.8	7.6	nr	Canada	(Heilman and Peabody Jr, 1981)
P. trichocarpa Clone Muhle Larsen	8	(55)	49	6.1	nr	Germany	(Bungart and Hüttl, 2004)
P trichocarpa x *P. deltoides* "Boelare"	8	(119)	31.8	4	nr	France	(Brahim et al., 2000b)
P. trichocarpa x *P. deltoides* "Beaupré"	9	27.6 (104)	110.4	12.3	4000	France	(Brahim et al., 2000a)
P. trichocarpa x *P. deltoides* "Hazendans"	4	4.6	45.6	11.4	nr	Belgium	(Laureysens et al., 2004)
P. balsamifera x *P. trichocarpa* "Balsam Spire"	5	nr	72.1	14.4	nr	Scotland	(Proe et al., 2002)
P. sp	**6**	**205 (117)**	**22.1**	**3.7**	**1080**	**Maryland, USA**	**(Felix et al., 2008)**
P. deltoides	**9**	**160 (423)**	**92.9**	**10.32**	**576**	**India**	**(Das et al., 2011)**
P. balsamifera	**nr**	**278 (250)**	**142**	**6.71**	**510**	**Sweden**	**(Johansson and Karacic, 2011)**
P. balsamifera	**nr**	**170.9 (195**	**nr**	**nr**	**nr**	**Alaska, USA**	**(Yarie et al., 2007)**
P. balsamifera	**2**	**1.5 (11.47)**	**11**	**5.5**	**7333**	**Alaska, USA**	**(Byrd et al., Unpublished)**

Note: nr indicates information not reported. Information in bold has been added to the original table.

fuel source. Research has been undertaken and successful poplar plantations exist in other parts of the world including Sweden, Belgium, USA, Canada, and India (Karacic et al., 2003, Laureysens et al., 2005b, Felix et al., 2008, Das et al., 2011, Peichl et al., 2006). While there has not been extensive research in Alaska, biomass estimation models have been developed in Scandinavia at latitudes similar to those in Alaska (Telenius, 1999, Johansson and Karacic, 2011). Poplar coppice research has generally used diameter at breast height (DBH) as the main parameter for biomass estimation, though when looking at smaller stem trees, diameter at 30cm above the ground (D30) has been employed (Ballard et al., 2000, Fang et al., 1999, Rytter and Stener, 2005).

Poplars have the ability to re-sprout after harvest (coppicing) or sudden top dieback. Some poplars such as *Populus trichocarpa* (black cottonwood), sprout from the stump, some sprout from root suckers *Populus tremuloides* Michx. (quaking aspen), and others from both the root and the stump (Dickmann et al., 2001). The practice of coppicing generally occurs in late fall or winter when the trees are dormant, whereas harvesting during the growing season can prove fatal (Zasada et al., 1981).

The concept of coppicing trees for biomass has been demonstrated successfully in New York (Volk et al., 2006, Adegbidi et al., 2001, Kopp et al., 1997a), Sweden (Nordh, 2005, Johansson et al., 2002), and elsewhere. The New York and Sweden experiments estimated an annual harvest varying from 9 – 11 dry tonnes ha^{-1} yr^{-1} in unfertilized or non-irrigated willow stands, and up to 27 dry tonnes ha^{-1} yr^{-1} with fertilization and irrigation (Abrahamson et al., 2002, Nordh, 2005). In Alaska, preliminary evaluations of willow plots in Fairbanks indicated biomass yields ranging from 0.2 – 0.3 dry tonnes ha^{-1} yr^{-1}, and biomass yields ranging from 0.3 – 0.7 dry tonnes ha^{-1} yr^{-1} for balsam poplar plots (Sparrow and Masiak, 2011 Unpublished data).

These results indicated that the Fairbanks yields were far lower than those observed in New York and Sweden. The short growing seasons, low soil moisture and poor soil nutrient content are potential limiting factors to the biomass production in Fairbanks. Nonetheless, feasibility studies indicated that several species of naturally occurring trees found in central Alaska may have potential as a biomass energy crop if grown under optimum conditions.

2.3 Growth Rate Studies

Growth rate studies of poplars have been undertaken throughout the world (Das et al., 2011, Johansson and Karacic, 2011, Laureysens et al., 2005b, Al Afas et al., 2008, Hytönen et al., 1987) with many studies conducted in the United States, Scandinavia, Europe, and India (Table 1). Young trees undergo a period of exponential growth, but their basal growth is generally linear until around age 4 years, when the growth changes to exponential (Norby and O'Neill, 1991, Felix et al., 2008). Poplar harvest frequencies range from 3 years (Rytter, 2012), 5-7 years (Hansen, 1991), to over 20 years (Persson, 1973, Das et al., 2011, Zabek and Prescott, 2006).

Maximizing growth of energy crops requires minimization of nutrient limitations. Rapidly growing poplars have a high nitrogen requirement, and intensively managed poplars can require around 150-250 kg ha^{-1} year^{-1} of nitrogen (Stanturf et al., 2001). Species selection based on net production per unit of nitrogen uptake rather than yield is an important consideration, especially when using low nutrient, or degraded soils (Singh and Behl, 1999). Soil testing is an important step in determining how much fertilizer is needed in the system to increase the yields. Isebrands and Karnosky (2001) posited that fertilizer addition does not affect the growth rates in the first growing season, but the slow release of nutrients does help to increase yields over time. Many growth studies do not include fertilizer in their growth rate research (Laureysens et al., 2005a, Dowell et al., 2009), whereas some studies have examined the best rates of fertilizer application for maximum growth (Karacic et al., 2003, Stanturf et al., 2001). Recommended sources of fertilizer for short rotation crops include commercial formulations and/or locally available organic fertilizer such as biosolids, fish waste, or even ash from boiler systems (Felix et al., 2008).

2.4 Estimation of Biomass

Calculation of forest biomass requires equations used to relate the mass of a tree to physical measurements easily obtained (Yarie et al., 2007). The use of these equations relies on the consistency of an allometric relationship between tree dimensions and its biomass (Jenkins et al., 2003). Common dimensions employed for allometric equations include diameter at 30cm (D30), and diameter at breast height (DBH), approximately equal to 1.4m above the ground. The equations are derived by correlating a readily-measured parameter (e.g., DBH) to the dry weight of the same sampled tree or stem (Yarie and Mead, 1988, Arevalo et al., 2007). Equation model development for biomass estimation has been studied extensively (Abrahamson et al., 2002, Ballard et al., 2000, Das et al., 2011, Yarie and Mead, 1988, Arevalo et al., 2007, Deckmyn et al., 2004, Jenkins et al., 2003). For larger trees (DBH > 2.5cm), the DBH measurement is often used. The D30 measure is often used for smaller trees, often because the tree being measured is less than 1.4m in height (Abrahamson et al., 2002). Many tables of equations exist for different species separating out size ranges of the tree dimensions, for example DBH at different diameters. This is done because at different life stages of the tree, it is likely it will grow at a different rate. Many equations are site specific, and a single equation will likely not work in all areas (Jenkins et al., 2003).

It has been observed that the biomass to stem diameter relationship can follow an exponential curve during the first six years of a poplar's life, though linear growth is also common (Felix et al., 2008, Ballard et al., 2000). Performing prediction validation calculations can be a way to ensure the best curve is fit to the data. Thus, the equation $W=ae^{bD}$, where W is the dry weight of the measured tree, a and b are constants, and D is diameter, was used to develop allometric equations based on the two predictors under the assumption of exponential growth. For linear models, this equation may be $W=aD-b$. These formulations were used for the estimation of biomass in this project, as described in subsequent sections.

A strong allometric relationship (r^2 approaching 1.0), can result in a cost effective measurement technique for estimating standing biomass (Ballard et al., 2000). Thus, allometric equations can be a useful tool for estimating growth rates of a woody crop being actively managed, and determining harvest rotations (Tahvanainen, 1996). Published allometric equations for poplars and other short rotation species have historically been developed for different species and hybrids at lower latitudes e.g. (Zianis and Mencuccini, 2004, Felix et al., 2008). In 2007, annual growth rate and allometric equations were developed for 17 *P. balsamifera* sampled in two sites in central Alaska (Yarie et al., 2007).

Numerous allometric equations have been developed to estimate standing biomass, including

$W = aD^b$ (Arevalo et al., 2007, Verwijst and Telenius, 1999), (1)

$W=a+bD$ (Ballard et al., 2000), (2)

$W=ae^{bD}$ (Volk et al., 2004b), and (3)

$W=aD+bD^2$ (Yarie and Mead, 1982) (4)

where W is the dry weight of the measured tree, a and b are constants, and D is diameter. In Microsoft EXCEL the equation $W=ae^{bD}$ is generated to develop the allometric equations based on a scatter plot of the predictors diameter at breast height (DBH) and diameter at 30cm (D30), and dry weight (Volk et al., 2004a). Published equations often provide the constants a,b for use on the equations. However the published constants are often limited to the region in which the equation was derived, so may not be appropriate for biomass estimation in Alaska. The higher latitudes and cool climate in Alaska can present unique growing conditions often including low rainfall, cool soils, and short growing seasons compared to conditions observed in lower latitudes. In order to accurately estimate the aboveground biomass in Alaska, regional biomass assessments must be undertaken to account for Alaska's diverse conditions.

The above allometric equations describe biomass available in the aboveground portion of the tree. However, biomass in trees is stored both above and below ground level

(Rytter, 2012, Zalesny et al., 2007). Belowground biomass is contained primarily in the root system including the main large root (tap root) and the smaller fine roots which spread into the surrounding soil. The aboveground biomass is the only portion harvested under SRC practices, and the belowground biomass is where some sequestered carbon remains stored (Rytter, 2012, Don et al., 2012). Woody SRC crops have been studied elsewhere for belowground biomass and carbon sequestration potential (Rytter, 2012, Benomar et al., 2012, Das et al., 2011, Peichl et al., 2006, Singh and Behl, 1999), though there is little data available relating to the CO2 sequestration and energy production capacity of woody SRC crops under conditions in central and Southcentral Alaska.

2.5 Lifecycle Assessment of Biomass Carbon

There are competing opinions expressed in the literature regarding whether biomass grown for energy effectively reduces atmospheric CO_2 emissions (Sims et al., 2006, Don et al., 2012, Tilman et al., 2006). For example, Tilman et al. (2006) suggested that burning biomass, which emits CO_2, is considered carbon-neutral only if the biomass is sustainably harvested. Others have suggested that carbon neutrality, a condition in which the amount of carbon emitted is equal to the amount of carbon stored or offset (Gunn et al., 2011), is difficult to quantify on a lifecycle analysis of a perennial energy crop (Don et al., 2012). A lifecycle analysis considers the entire system from planting, fertilizing, harvesting, feedstock production, and burning, including all of the tools, vehicles, fuel, and fertilizer used for the biomass and feedstock production (Johnson, 2009). It has been suggested that the net CO_2 stored during biomass growth can essentially be lost during feedstock production, especially transportation (Don et al., 2012). In New York, a study of willow production indicated that 55 units of biomass energy was produced for every unit of fossil fuel used, though this study did not include the transportation and purchase costs of fertilizers and other materials for use in the study (Heller et al., 2003). However, this did suggest that the use of locally harvested wood could be a way of keeping carbon emissions to a minimum.

The lifecycle costs of a biomass energy system need to be taken into account when evaluating sustainability (Gonzalez-Garcia et al., 2012). Gonzalez-Garcia et al. (2012) offer an example of one 20-year lifecycle assessment in a Swedish commercial willow plantation of 10,000 trees per hectare (and harvesting 10t ha^{-1} yr^{-1} dry chips). In this plantation, a total of 1070 kg N ha^{-1}, 8L ha^{-1} each of Glyphosphate (36%) and Gardoprim (49%) is applied, and a total of 183 gallons ha^{-1} of diesel is used in crop production for biofuels and bioelectricity. The results showed the lifecycle assessment favoring biothanol production over bioelectricity after incorporating all of the harvesting and refining processes. These inputs need to be taken into account when evaluating the sustainability and energy balance of a woody biomass plantation. The carbon emitted during the production of commercial fertilizer is quite large (Keoleian and Volk, 2005), and an alternative to commercial fertilizer may reduce lifecycle carbon emissions.

A crop's ability to sequester carbon is an important factor to consider when using the trees as a renewable energy to replace fossil fuels. Knowing the amount of carbon stored in the aboveground and the belowground biomass of poplar trees can be a starting point in defining how much carbon is being removed from the system when harvested. A Canadian study found in a 13 year old mixed stand of poplar and spruce trees that 85% of the biomass for both species was stored aboveground, with the remaining 15% stored belowground in the root system. Of the poplar's total biomass, 44% was stored in the leaves and branches, and 41% in the bole or trunk. The spruce trees in comparison stored 63% of the total biomass in the leaves and branches, and 22% in the bole or trunk (Peichl et al., 2006).

2.6 Nutrient Cycling

Fast growing biomass crops are generally planted on degraded lands, as the more fertile lands are often taken up for more valuable crops or other profitable land uses (Felix et al., 2008, Gonzalez-Garcia et al., 2012, Singh and Behl, 1999). In Europe, a move from a highly subsidized overproducing food cropping system has left a higher proportion of fertile land available for energy crops. A poplar study in Sweden demonstrated that on fertile lands, any additional nitrogen added to the system produced no significant increase in aboveground biomass accumulation (Telenius, 1999). Consequently, energy cropping practices could potentially be expanded in Sweden and elsewhere in Europe without requiring excessive fertilization. Unfortunately, not all regions seeking to expand energy crop development have the benefits of fertile lands, and even fertile lands will be depleted of nutrients under intensive management (Singh and Behl, 1999, Zalesny et al., 2007).

Growth studies have demonstrated that poplars on nutrient-poor soils are responsive to fertilization, however the efficiency of fertilization can be improved by identifying the particular nutrient needs of various poplar species (Rogers et al., 2012). Rogers et al. (2012) found that for a poplar tree to be the most productive, the internal nutrient concentrations should be stable and that additional nutrient addition rates should match plant uptake rates.

Trees store the majority of their aboveground nutrients in their leaves, followed by the twigs, branches and the bole. The majority of the belowground nutrients are stored in the fine roots, followed by the lateral roots, and the tap root (Das and Chaturvedi, 2009). In India, a *P. deltoides* nutrient cycling study found the total nutrients associated with foliage production for a three year old, poplar plantation were 51.7 N, 3.1 P and 19.5 K kg ha^{-1}year^{-1}. Of this 28.1 N, 1.2 P and 9.0 K kg ha^{-1} year^{-1} were cycled back from senescing leaves. This recycling of nutrients supported production of new foliage and diminished the demand of nutrients from soil (Das and Chaturvedi, 2009). Increasing nutrient availability while allowing nutrients to return to the soil are important management considerations to foster nutrient cycling in plantations (Isebrands and Karnosky, 2001).

Chapter 3 - Materials and Methods

3.1 Site Description

The study site was an experimental 10m x 20m vegetated lysimeter located on Joint Base Elmendorf Richardson (JBER) in Anchorage, Alaska. The lysimeter was previously utilized for a study designed to test the efficacy of poplar plantations used as landfill covers in Southcentral Alaska (Schnabel et al., 2012). The soil materials were obtained from local forest areas being cleared for housing. The bottom soil layer (1.4m) was a mixture of sand, gravel, and silt loam. The top soil layer (0.6m) was locally derived silt loam soil, with woodchips and forest organic matter mixed in.

Sapling poplar trees, locally acquired from nearby forests, were harvested with roots intact and planted in pots in fall 2003, and transplanted to the JBER site in spring 2004 (Figure 1). The planting mixture included *Populus balsamifera* (80%), *P. tremuloides*

(10%), and *Salix sp*. (10%). The trees were planted at 1.2m intervals, equivalent to 7330 trees ha^{-1}. In addition to these trees, four rows of trees were planted on the perimeter of the site to minimize edge effects (Schnabel et al., 2012).

Figure 1 *Populus balsamifera* saplings ready to plant at the JBER site

3.2 Estimate of Aboveground Biomass

In summer of 2010, each stem of the 128 poplar and aspen trees within the study area was measured for DBH and D30 using digital calipers. In March of 2011, before the trees had started to resume growth after winter dormancy, the entire aboveground biomass on the site was harvested at 30cm above ground level using a chainsaw. The harvested biomass was measured for total height using a tape measure, wet weight was taken using a field scale, and diameter measurements were taken at DBH and D30 using digital calipers. One *P. balsamifera* was retained from each row (sixteen total) and stored in Hessian sacks, dried at 60^{o}C and re-weighed for dry weight biomass estimations. Measurements taken on the harvested material were used to correlate the standing biomass measurements with the dry weights, and create allometric equations. Allometric equations were created for relationships between D30, DBH, and total height against dry weight using the scatter plot feature in Excel. Exponential or linear trend lines were applied to the scatter plots as a best fit relationship, and from the relationship, an allometric equation was derived.

Figure 2 Study area on Joint Elmendorf Richardson in July, 2010

Figure 3 Study area after first harvest

Figure 4 Regrowth of *P. balsamifera* after two years

Harvested trees were chipped through a Steinmax 1800 wood chipper. Chipped trees and roots were stored in cotton bags for further processing. Subsamples of the chipped trees and roots were obtained by taking four grab samples of chips from four different areas of each bag. The subsamples of each tree were combined and passed through a 1mm mesh in a Wiley Mill Standard Model #3 grinder. Carbon and nitrogen content analyses were performed on a LECO TruSpec CN analyzer. The samples were combusted at 950°C and the combusted gases were analyzed for CO_2 by an infrared detector, and for nitrogen by a thermal conductivity cell. Ash free dry mass (AFDM) was determined gravimetrically on an analytical balance by drying the samples at 60°C for 24 hours, 105°C for 24 hours, and ash at 550°C for 420 minutes using a Thermolyne Type 30400 muffle furnace. Energy content of ground tree samples was analyzed in a Parr Plain Jacket bomb calorimeter (model number 1341). Samples were processed for total combusted energy expressed as kJ/kg.

After the first harvest, the plot was divided into four quadrants. Fertilizer was added to two diagonally adjacent quadrants, and two diagonally adjacent quadrants were retained as controls. A slow release fertilizer was added at a rate of 112 Kg N ha^{-1}, and 25 Kg P ha^{-1}, and 60 Kg K ha^{-1}. T-test statistical analyses ($P<0.05$) were used to compare fertilized quadrants to unfertilized quadrants.

In 2012, three trees were randomly selected in each quadrant. On the selected trees, all stem diameters were measured, and three stems were randomly selected for harvest and allometric equation calculation. All of the remaining stems from the measured trees were harvested, dried, and all stems were weighed together for complete tree measurements.

3.3 Estimate of Belowground Biomass

In the buffer zone on the perimeter of the study site, three poplars were harvested and analysed for total above and belowground biomass to be used in a carbon balance model. The entire belowground material, to a depth of 30cm and halfway between adjacent trees, was removed from the basal area of the three trees. Roots were cleaned manually and dried to $60^{o}C$ for 24 hours, and weighed for total dry weight prior to chipping. Root samples were included with the aboveground tree samples tested for carbon, nitrogen, ash free dry mass (AFDM), and energy.

Random soil samples (ten per quadrant) were obtained in the fall of 2012 at depths of 0 - 15 cm, and 15 – 30 cm below the surface in the fertilized and unfertilized quadrants of the study site. The soil samples were passed through a 2 mm screen, analyzed for total carbon and nitrogen, inorganic nitrogen, extractable phosphorous, and extractable potassium. The soil in the buffer zone differed in texture to that of the main study site.

Chapter 4 – Results and Discussion

4.1 Aboveground Biomass Production

The aboveground biomass collected in the first harvest measured 21,550 kg ha^{-1} (Table 2). At the time of transplant, the age of the trees was not determined, and the mass of the trees was not quantified. Consequently, we could not precisely quantify the annual biomass accumulation rate during the first rotation. However, the maximum theoretical rate, based upon the total biomass measured after seven years, was 3,079 kg ha^{-1} yr^{-1}. Assuming that the mass of the trees at planting was minimal compared to the mass of the trees at harvest, the biomass accumulation rate over the seven-year first rotation was slightly less than that. Consequently, the first rotation biomass accumulation rate was lower than the rate observed during the two-year second rotation (5,530 kg ha^{-1} yr^{-1}). This result is not surprising, as the trees growing in the second rotation had the advantage of a well-developed root system. An additional difference between the first and second rotation relates to the number of stems per tree. While the first rotation trees were generally limited to one or two relatively large diameter stems, the second rotation trees had from 10 to 38 small diameter stems.

With respect to stem diameter, the average D30 at the first harvest was 34 mm, and the first year regrowth average D30 was 9.4 mm. The D30 of the regrowth after the second growing season was 13.7 mm (Table 2).

Table 2 Measured biomass accumulation of *P. balsamifera* at first harvest and second harvest.

Stand age (Years)	Average D30 (mm)	Average DBH (mm)	Average Tree Total Height (cm)	Average Tree Dry Weight (kg)	Average Biomass per Hectare (kg)	Average Annual Biomass per Hectare (kg)
7+	34.1	27.0	449.1	2.9	21,550	<3,086
1st year Regrowth	9.4	7.6	nr	nr	nr	nr
2nd year Regrowth	13.7	11.5	166.1	1.5	11,060	5530

Note: Tree height, weight, and biomass were not measured for the 1st year regrowth

The information presented in Table 2 indicates that growing biomass from locally sourced poplars may be an option to offset the use of diesel heating fuel. For example, the energy content of 1 kg of dried wood was reported to be 19,684 kJ/kg, while the energy content of heating oil is 42,790 kJ/kg (Wright et al., 2006). Therefore, after a 7+ year rotation, enough wood was produced per hectare to offset 9,913 liters of heating fuel. This plantation was grown without fertilization and with very little management costs. A planted crop will incur costs of soil preparation, planting, and initial fertilizing, which could become cost prohibitive in some areas. Though, a natural stand of trees may not yield the same result, it could keep management costs to a minimum.

4.2 Allometric Relationships

The relationship between stem diameter and stem/branch dry weights for the first rotation trees are plotted in Figures 5 and 6. The allometric equation in Figure 5 illustrates a moderately strong relationship between D30 and dry weight of the aboveground biomass (R^2= 0.8736). The relationship between DBH and dry weight (Figure 6) is very similar to that of D30 (R^2 = 0.8653). Both of these R^2 values suggest a moderately strong relationship between diameter of the tree at both DBH and D30 and total tree biomass. Most poplar studies use DBH for their biomass estimations due to the large size of the main stem (Felix et al., 2008, Zalesny et al., 2007). Unpublished preliminary growth data indicate that DBH in Alaska tends to be smaller than those in data from studies published elsewhere around the world, and experience under this project revealed that D30 measurements were approximately equal in their ability to predict biomass. Diameter at 30cm is used often in willow growth studies (Tahvanainen, 1996, Verwijst and Telenius, 1999, Kopp et al., 1997b).

The relationship between total height and dry weight was not as strong as D30 and DBH (R^2 = 0.7699). This suggests that height was not the best predictor of aboveground biomass in this study.

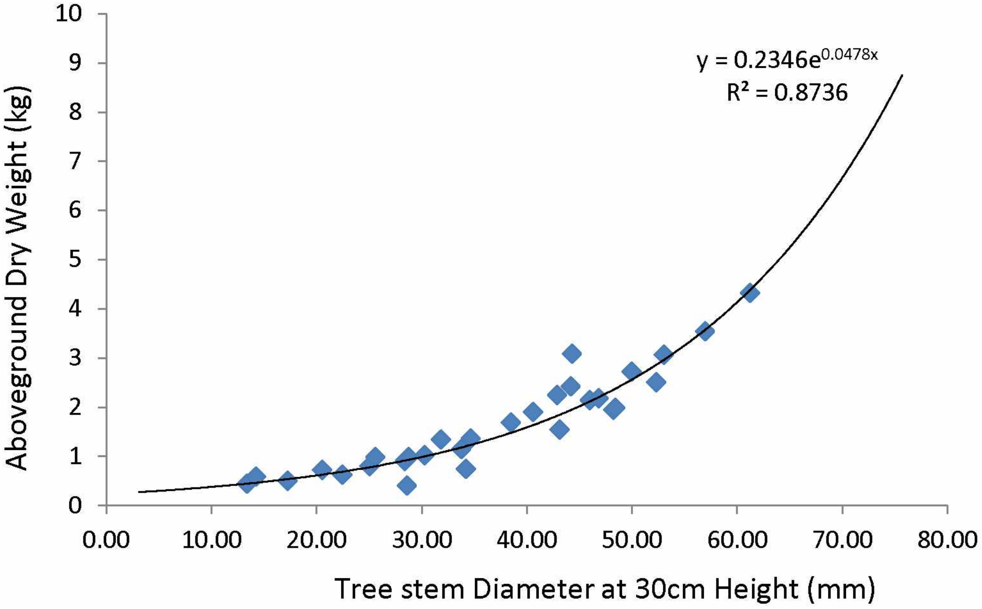

Figure 5 An exponential allometric relationship between diameter at 30cm (D30) above ground and dry weight of *P. balsamisfera* for 7+ year old trees.

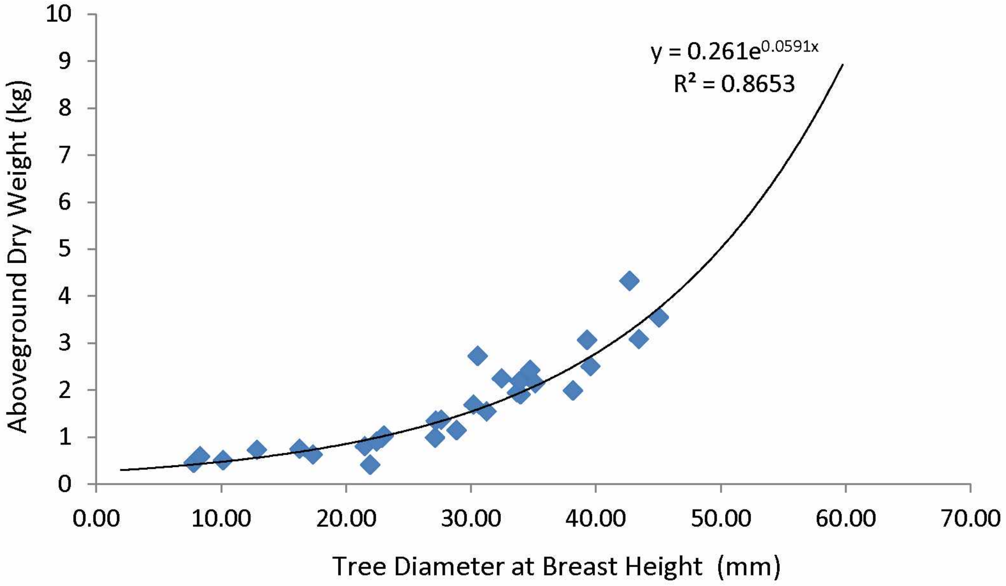

Figure 6 An exponential allometric relationship between diameter at breast height (DBH) and dry weight of *P. balsamisfera* for 7+ year old trees.

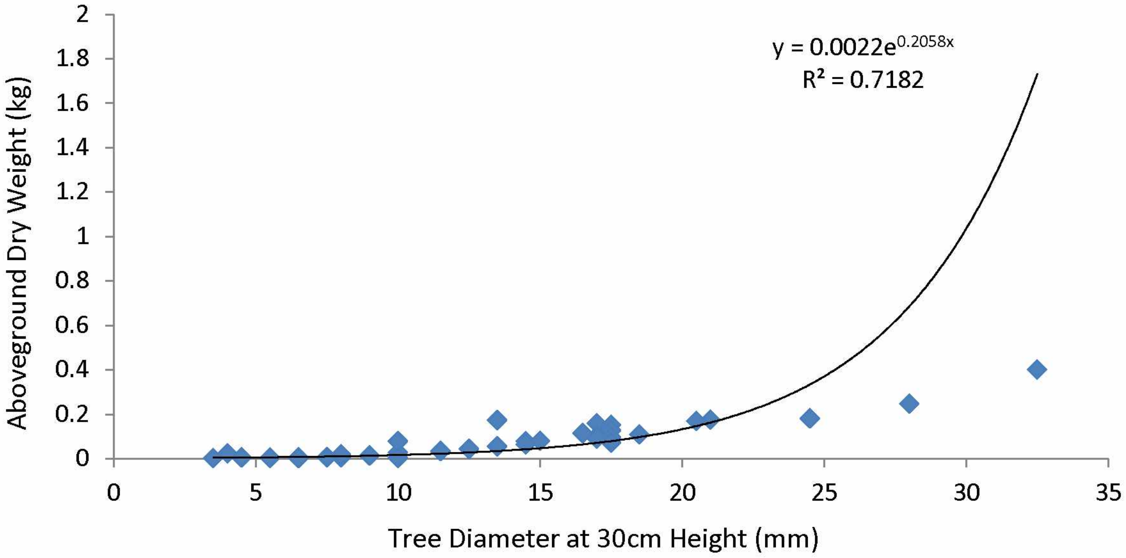

Figure 7 An exponential allometric relationship between D30 and dry weight of *P. balsamifera* at 2 years after harvest.

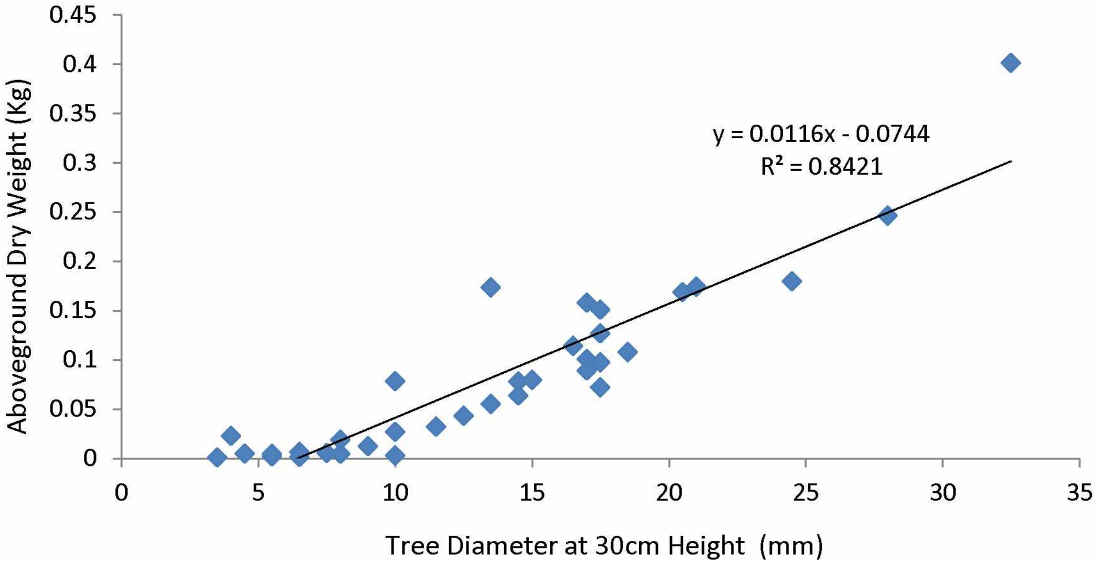

Figure 8 A linear allometric relationship between D30 and dry weight of *P. balsamifera* at 2 years after harvest.

For the first harvest, exponential equations best described the data, whereas in the second harvest, the stems were best described by a linear equation. This agrees with previous findings suggesting that the small diameter of the regrown stems don't often fit well into an exponential model for biomass (Abrahamson et al., 2002, Ballard et al., 2000, Felix et al., 2008, Norby and O'Neill, 1991). In the first years of growth, energy is put into increasing the tree height, and branching increases as the tree ages. This may explain the early linear growth, and a later exponential growth.

The allometric equation for the 2-year regrowth after harvest is best described by a linear equation with an R^2 of 0.8421 (Figure 7). Using a Mean Square Error of the Prediction (MSEP) equation suggested in Ballard et al. (2000):

$$\mathrm{MSEP} = \Sigma(y_i - \acute{y}_i)^2/m \qquad \text{(Neter et al., 1996)} \qquad (5)$$

where m is the number of observations, and the y_is are the observed and predicted biomass, we found that the linear model best predicted the biomass with an MSEP of $5.589E^{-9}$, whereas the exponential model MSEP was $3.50E^{-5}$. In the MSEP validation technique, an MSEP value of zero suggests optimum predictability, but is never reached (Neter et al., 1996).

Another tool used to assess the validity of the model was the Bias Correction Factor (BCF):

$$\mathrm{BCF} = \frac{\overline{w}}{\hat{w}} \qquad \text{(Snowdon, 1991)} \qquad (6)$$

where $\overline{w}$ is the mean of sampled biomass, and $\hat{w}$ is the mean of predicted sample biomass. The linear regression model corrected by the BCF equation produced a predicted biomass 100% the same as the measured, while the exponential regression model corrected by the BCF equation underestimated the biomass by 43%.

4.3 Elemental Composition and Energy Content of Harvested Trees

Nitrogen and carbon concentration in the aboveground biomass did not change between the two harvest intervals (Table 3). The percent of ash free dry mass was also very similar in the two harvests. Similarly, the energy content and carbon accumulation rates did not change.

Table 3 Total nitrogen, carbon, ash free dry mass, and energy content of aboveground biomass

Tree age	Nitrogen %	Carbon %	Ash Free Dry Mass %	Energy content kj/kg	Energy per hectare MJ/ha	Equivalent liters Diesel /ha
7+ years	0.62 (±0.006)	48.73 (±0.017)	94.87 (±0.011)	18,750 (±363)	404,063	9,913
Regrowth Fertilized	0.72 (±0.19)	49.67 (±0.32)	95.10 (±0.43)	19,762 (±93)	218,567	5,740
Regrowth Un-Fertilized	0.62 (±0.02)	49.66 (±0.43)	95.11 (±0.19)	19,608 (±220)	216,864	5,700

The data represented in Table 3 provided the information necessary to test the hypotheses associated with this study. The first hypothesis (H_{01}) posited that the energy and carbon content of the second rotation regrowth would be the same as the initial aboveground biomass. Results indicate that the carbon concentration in first rotation biomass did not differ significantly from that of the fertilized or unfertilized quadrants in the second rotation ($P \geq 0.05$). However, a T-test assuming equal variances indicated that energy content of the wood in the second rotation was significantly higher ($P \leq 0.000025$) compared to that of the first rotation. Thus, the null hypothesis was not rejected with respect to carbon content, but was rejected with respect to energy content. The finding of higher energy content in the regrowth could be related to the higher content of extractives, or non-cell wall components such as fatty acids in young trees (Kačík et al., 2012). While we did not measure the energy content of different stem sections, the branches of hardwood species generally have a higher energy content per mass than that of the bole (Singh and Behl, 1999).

4.4 Effects of Fertilizer on Second Harvest Rotation Trees

The second hypothesis (H_{02}) stated that after the initial harvest, the nitrogen fertilizer application will have no effect on the biomass regrowth. As indicated in Table 4, the poplars in second rotation were unaffected by nitrogen fertilizer application ($P \geq 0.05$) for all parameters. Dry weight and measurements at D30 and DBH did not vary between the fertilized and unfertilized areas, and there was no significant difference between the ash free dry mass between the two treatments. Thus, the results did not allow us to reject the null hypothesis H_{02}.

Table 4 Measurements of second rotation trees in fertilized and unfertilized quadrants.

Treatment	Unfertilized (mean)	Fertilized (mean)	DF	P-Value
Mean Dry weight (kg)	1.6	1.5	1	0.48
D30 (mm)	14	14	1	0.41
DBH (mm)	11	14	1	0.092
Height (cm)	194	139	1	0.173
Ash Free Dry Mass %	95	95	1	0.49
kJ/kg	19,608	19,761	1	0.08

While the nitrogen fertilization did not impact biomass regrowth, there was an observed difference in soil carbon between the fertilized and unfertilized plots (Table 5). The carbon concentration in the upper 15cm of soil of the fertilized quadrants was significantly higher ($P \leq 0.05$) than the soil in the unfertilized quadrants. This could be related to increased growth of non-target vegetation (i.e., weeds) in the fertilized quadrants. Alternatively, the increase in carbon could be explained by an initially higher carbon concentration in some areas of the soil before the trees were planted. There was no difference in total nitrogen in the upper 15cm of the soil and, likewise, the inorganic NO_3^- and NH_4^- were not significantly different in any part of the sampled soil profile. The wood energy content of the fertilized quadrants showed no significant difference to the unfertilized quadrants.

Table 5 Statistical analysis of soil nutrients

Measurement	Depth (cm)	Fertilized / Unfertilized (mean)	DF	P-Value
Total Soil Carbon (%)	0-15 15-30	3.2 / 2.4 2.7 / 2.7	1	0.003 0.484
Total Soil Nitrogen (%)	0-15 15-30	0.2 / 0.2 0.2 / 0.2	1	0.59 0.439
N NO_3^- (PPM)	0-15 15-30	0.4 / 0.1 1.3 / 1.1	1	0.293 0.273
N NH_4^- (PPM)	0-15 15-30	1.6 / 2.1 2.7 / 1.6	1	0.111 0.230

As indicated above, weeds in the fertilized quadrants appeared more abundant than in the unfertilized quadrants. The surface broadcast of slow-release fertilizer may have increased production of the grassy understory rather than the woody biomass. A previous study suggested direct application of a slow release fertilizer to the base of the tree stem upon planting for best fertilization results, ensuring more nutrient uptake by the targeted trees, rather than weeds (Guillemette and DesRochers, 2008). More research is needed to fully understand the nutrient depletion and fertilizer application rates in a SRC crop.

4.5 Destructive Analysis and Carbon Balance of Buffer Zone Trees

As we sought to maintain the integrity of the trees within the study area, we used trees in the surrounding buffer zone for destructive sampling of root material. All work relating to the belowground biomass was conducted in the buffer zone.

Analysis of the root biomass indicated that the root dry weight for each tree was representative of the aboveground dry weight. Tree 1, for instance, had the lowest weight of aboveground biomass as well as the lowest root biomass of the three trees (Table 6). The root carbon content was found to be lower than the aboveground tree carbon in all instances. However, some soil particles may have remained in the root samples during separation. During root separation, recently living roots were separated from the soil, rock and other woody debris fractions. While all attempts were made to retrieve fine roots from the soil, some fine root material was lost during the separation. And, while all attempts were made to remove all soil material from the roots, some small particles remained. Soil was excavated to 30 cm depth; this assumes that there was no significant carbon sequestration below 30cm depth. Rytter (2012) suggests that in cooler soils carbon sequestration rates decline with soil depth.

Table 6 Tree root analysis of three trees from the buffer zone.

	Tree 1	Tree 2	Tree 3
Tree Dry Weight kg	1.46	4.0	3.76
Stump Dry Weight kg	0.2	0.48	0.40
Root Biomass kg	0.66	1.499	1.341
Root Energy kJ/kg	18,493	16,603	18,169
Tree Carbon %	48	48	48
Root Carbon %	44	44	46
Root AFDM %	85.33	94	90.49

Using the data from the aboveground biomass harvested, and the belowground root biomass estimations, a simple carbon content model was determined for the project site.

The following equation was to understand the carbon balance in the tree system:

$$C_s = (C_a + C_b) - C_h \tag{1}$$

Carbon balance in the study area will account for the carbon stored in the tree system, and removed (harvested) from the system where C_s is stored carbon; C_a is the carbon stored in the aboveground biomass; C_b is the carbon stored in the belowground biomass; and C_h is the carbon harvested in the aboveground biomass (Table 7). Unfortunately, soil samples beneath these trees were not analyzed for non-root carbon content, therefore a full carbon balance could not be completed.

Table 7 Carbon storage in harvested trees using average aboveground carbon (48%) and belowground carbon (44%) values.

Tree Sample	Tree Total Carbon (kg)	Aboveground Carbon (kg) C_a	Root Carbon (kg) C_b	Harvested Carbon (kg) C_h	Carbon Stored (kg) C_s	Total Carbon stored (kg/ha)
Tree 1	1.09	0.80	0.29	0.70	0.39	5,334
Tree 2	2.81	2.15	0.66	1.92	0.89	
Tree 3	2.62	2.00	0.62	1.80	0.79	

While there were not enough data gathered to complete a full carbon balance, it is interesting to note that the average mass of aboveground carbon harvested per tree was approximately 1.65 kg, while the average mass of carbon stored in the roots and remaining stump per tree was 0.7 kg. Thus, for every unit of carbon returned to the atmosphere through burning, roughly one-half unit was sequestered at the plantation site. However, this approximation does not account for the carbon exuded from the roots into the soil during decomposition, the fine roots that were missed during excavation and separation, or the carbon stored in the leaf litter surrounding the tree. In the future, it would be useful to conduct a follow-up study to determine how much and at what rate the carbon remaining on site cycles back to the atmosphere. This would lend insight into the question of carbon neutrality.

Under many biomass lifecycle assessments, the carbon emitted during burning is accounted as zero. With an increase in biomass harvested for energy, the carbon that might have been stored in the trees and soil would actually be released to the atmosphere (Zanchi et al., 2012). Moreover, this increase in harvesting would likely result in a younger forest, which inherently stores less carbon than a more mature forest, and has potentially lower carbon pools (Schulze et al., 2012). While the carbon that is released from biomass is 'new' and not from fossil sources, it is still carbon and that carbon needs to accounted for in lifecycle assessments (Djomo et al., 2011).

Chapter 5 – Conclusions and Recommendations

Destructive sampling of *P. balsamifera* under short rotation, on an experimental landfill cap in Southcentral Alaska, demonstrated that exponential allometric equations best described the aboveground biomass of the 7+ year old trees, whereas linear equations best described the 2-year old regrowth. Development of accurate, non-destructive, allometric equations is important to ensure low-cost estimation of standing biomass. It was concluded that both DBH and D30 are sufficient to produce a strong relationship with dry weight of the same stem. The equations and coefficients developed for *P. balsamifera* in this thesis are specific to the study site in Southcentral Alaska. Use of the equations in other areas of Alaska may not yield accurate results, but are likely more appropriate than use of equations developed in temperate regions. Regional-specific equations should be developed for *P. balsamifera* in all areas of the state where short rotation coppice cropping is being considered.

Nitrogen fertilizer application had no effect on the biomass accumulation of the regrowth. While nitrogen fertilizer didn’t affect the growth of the *P. balsamifera* during this study, continued harvest may deplete nutrients in the soil and may need to be replenished to maintain optimal biomass growth. The fertilizer application may have benefitted non-target species in the study. Management of non-target, understory species may allow more uptake of nutrients by the target species. Further study is recommended for fertilization and other stand management practices applicable to short rotation energy crops in Alaska.

Carbon concentration in the aboveground biomass was not significantly different between the first and second harvests. However, the soil carbon was significantly higher in the fertilized quadrants, due perhaps to the increased understory growth. The uptake of applied fertilizer by the non-target species may have increased soil carbon in the fertilized quadrants. Energy content of the wood was significantly higher in the second rotation as young stems can have a higher concentration of non-cell wall materials that are high in fatty acids.

The accumulated biomass during the first 7+ years of growth in this study would have potentially offset approximately 9,913 liters of diesel fuel per hectare. With more study on rotation lengths, as well as fertilizer application methods and rates, there is potential for greater annual biomass accumulation. Longer rotation lengths, perhaps ten to twenty years, may be more economical to wood users. A biomass heating, and a combined heat and power system, is designed to use a specific diameter of wood. Some systems use chipped wood, whereas others may use cord wood. The system is generally dictated by the size and rotation lengths of the surrounding forest resource. This size will determine how long the rotation lengths are required under the environmental conditions. Fertilizer application could potentially decrease rotation lengths by increasing the rate at which biomass is accumulated.

In a short rotation coppice crop, the carbon released per unit of fossil energy input may be less than that of coal or diesel. A carbon neutral biomass system might be possible if the harvesting can be conducted close to the boiler, and require little transportation. A locally sourced fish processing waste, human or animal waste, or other nitrogen source could be used as fertilizer if applied at the correct application rates; soil tests and fertilizer material tests would need to be conducted to determine nutrient depletion rates.

We do not yet know if SRC will be viable in Alaska. Planting a whole crop may or may not be the best strategy for short rotation forestry in Alaska depending on comparative costs of an SRC versus low cost management of natural stands. Moreover, other species may be better suited to different regions of Alaska. Indeed, managing the locally available, existing trees with established roots may be a more efficient method. A local forest inventory and land ownership details provided by Alaska Department of Natural Resources, Department of Forestry or by a local tribal council may provide species quantities and prescribed rotation lengths. These rotation lengths are generally established to return the highest yield.

This study produced a set of allometric equations and growth rate measurements for *P. balsamifera* under short rotation cropping. The allometric equations produced here may not be accurate in all areas of Alaska, but could be used as a guide. The methods used in this study could be replicated elsewhere in Alaska and would be an important process in determining growth rates and developing allometric equations for biomass estimation. Further replication of this study would be useful in Alaska as biomass energy is being employed in a growing number of communities. Short rotation crops of *P. balsamifera* may be a way to ensure a sustainable harvest of biomass fuel for boilers though may not be economical in some areas to establish a dedicated crop area. Managing the naturally occurring poplar species for short rotation could prove just as beneficial, and developing allometric equations would be vital.

References

ABRAHAMSON, L. P., VOLK, T. A., KOPP, R. F., WHITE, E. H. & BALLARD, J. L. 2002. Willow Biomass Producer's Handbook. Syracuse, NY: State University of New York.

ADEGBIDI, H. G., VOLK, T. A., WHITE, E. H., ABRAHAMSON, L. P., BRIGGS, R. D. & BICKELHAUPT, D. H. 2001. Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York State. *Biomass and Bioenergy,* 20**,** 399-411.

AL AFAS, N., MARRON, N., VAN DONGEN, S., LAUREYSENS, I. & CEULEMANS, R. 2008. Dynamics of biomass production in a poplar coppice culture over three rotations (11 years). *Forest Ecology and Management,* 255**,** 1883-1891.

ALASKA DEPARTMENT OF COMMERCE COMMUNITY AND ECONOMIC DEVELOPMENT 2012. Current Community Conditions Alaska Fuel Price Report. http://www.bbna.com/ak%20state/FuelWatch_2012_January.pdf.

ALASKA ENERGY AUTHORITY 2010. Alaska Energy Plan: A Guide for Alaskan Communities to Utilize Local Energy Resources. http://www.akenergyauthority.org/alaska-energy-plan.html.

AREVALO, C. B. M., VOLK, T. A., BEVILACQUA, E. & ABRAHAMSON, L. 2007. Development and validation of aboveground biomass estimations for four *Salix* clones in central New York. *Biomass & Bioenergy,* 31**,** 1-12.

ARMSTRONG, A., JOHNS, C. & TUBBY, I. 1999. Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop. *Biomass and Bioenergy,* 17**,** 305-314.

BALLARD, B. D., STEHMAN, S. V., BRIGGS, R. D., VOLK, T. A., ABRAHAMSON, L. P. & WHITE, E. H. 2000. Aboveground biomass equation development for five *Salix* clones and one *Populus* clone. New York Center for Forestry Research and Development (NYCFRD-99-01). Syracruse, NY: SUNY-ESF.

BENOMAR, L., DESROCHERS, A. & LAROCQUE, G. R. 2012. The effects of spacing on growth, morphology and biomass production and allocation in two hybrid poplar clones growing in the boreal region of Canada. *Trees-Structure and Function,* 26**,** 939-949.

BLACKMON, B. G., BAKER, J. B. & COOPER, D. T. 1979. Nutrient use by three geographic sources of eastern cottonwood. *Canadian Journal of Forest Research,* 9**,** 532-534.

BOWERSOX, T. W. & WARD, W. W. 1976. Growth and yield of close-spaced, young hybrid poplars. *Forest Science,* 22**,** 449-454.

BRAHIM, B. M., GAVALAND, A. & CABANETTES, A. 2000a. Generalized allometric regression to estimate biomass of *Populus* in short-rotation coppice. *Scandinavian Journal of Forest Research,* 15**,** 171-176.

BRAHIM, B. M., GAVALAND, A. & GAUVIN, J. 2000b. Growth and yield of mixed polyclonal stands of *Populus* in short-rotation coppice. *Scandinavian Journal of Forest Research,* 15**,** 605-610.

BUNGART, R. & HÜTTL, R. F. 2004. Growth dynamics and biomass accumulation of 8-year-old hybrid poplar clones in a short-rotation plantation on a clayey-sandy mining substrate with respect to plant nutrition and water budget. *European Journal of Forest Research,* 123**,** 105-115.

BYRD, A. G., SCHNABEL, W. E., SPARROW, S. D. & MASIAK, D. T. Unpublished. Biomass accumulation of *Populus balsamifera* as a short rotation coppice crop in Southcentral Alaska. Unpublished.

CZAPOWSKYJ, M. M. & SAFFORD, L. O. 1993. Site preparation, fertilization, and 10-year yields of hybrid poplar on a clearcut forest site in eastern Maine, USA. *New Forests,* 7**,** 331-344.

DAS, D. K. & CHATURVEDI, O. P. 2009. Energy dynamics and bioenergy production of *Populus deltoides* G-3 Marsh plantation in eastern India. *Biomass & Bioenergy,* 33**,** 144-148.

DAS, D. K., CHATURVEDI, O. P., JABEEN, N. & DHYANI, S. K. 2011. Predictive models for dry weight estimation of above and below ground biomass components of *Populus deltoides* in India: Development and comparative diagnosis. *Biomass & Bioenergy,* 35**,** 1145-1152.

DEBELL, D. S., CLENDENEN, G. W., HARRINGTON, C. A. & ZASADA, J. C. 1996. Tree growth and stand development in short-rotation *Populus* plantings: 7-year results for two clones at three spacings. *Biomass and Bioenergy,* 11**,** 253-269.

DECKMYN, G., LAUREYSENS, I., GARCIA, J., MUYS, B. & CEULEMANS, R. 2004. Poplar growth and yield in short rotation coppice: model simulations using the process model SECRETS. *Biomass & Bioenergy,* 26**,** 221-227.

DICKMANN, D. I., ISEBRANDS, J. G., BLAKE, T. J., KOSOLA, K. & KORT, J. 2001. Physiological ecology of poplars. *In:* DICKMANN, D. I., ISEBRANDS, J.G., ECKENWALDER, J.E., RICHARDSON, J. (ed.) *Poplar Culture in North America. Ontario, Canada: NRC Research Press.*

DJOMO, S. N., EL KASMIOUI, O. & CEULEMANS, R. 2011. Energy and greenhouse gas balance of bioenergy production from poplar and willow: a review. *Global Change Biology Bioenergy,* 3**,** 181-197.

DON, A., OSBORNE, B., HASTINGS, A., SKIBA, U., CARTER, M. S., DREWER, J., FLESSA, H., FREIBAUER, A., HYVONEN, N., JONES, M. B., LANIGAN, G. J., MANDER, U., MONTI, A.,

DJOMO, S. N., VALENTINE, J., WALTER, K., ZEGADA-LIZARAZU, W. & ZENONE, T. 2012. Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. *Global Change Biology Bioenergy,* 4**,** 372-391.

DOWELL, R. C., GIBBINS, D., RHOADS, J. L. & PALLARDY, S. G. 2009. Biomass production physiology and soil carbon dynamics in short-rotation-grown *Populus deltoides* and *P. deltoides* x *P. nigra* hybrids. *Forest Ecology and Management,* 257**,** 134-142.

FANG, S., XU, X., LU, S. & TANG, L. 1999. Growth dynamics and biomass production in short-rotation poplar plantations: 6-year results for three clones at four spacings. *Biomass and Bioenergy,* 17**,** 415-425.

FELIX, E., TILLEY, D. R., FELTON, G. & FLAMINO, E. 2008. Biomass production of hybrid poplar (*Populus* sp.) grown on deep-trenched municipal biosolids. *Ecological Engineering,* 33**,** 8-14.

GARBER-SLAGHT, R., SPARROW S.D., MASIAK D.T. & HOLDMANN, G. 2009. Opportunities for woody biomass fuel crops in interior Alaska. https://www.uaf.edu/files/snras/MP_08_09.pdf, University of Alaska Fairbanks, School of Natural Resources and Agricultural Sciences.

GONZALEZ-GARCIA, S., IRIBARREN, D., SUSMOZAS, A., DUFOUR, J. & MURPHY, R. J. 2012. Life cycle assessment of two alternative bioenergy systems involving *Salix sp.* biomass: Bioethanol production and power generation. *Applied Energy,* 95**,** 111-122.

GUILLEMETTE, T. & DESROCHERS, A. 2008. Early growth and nutrition of hybrid poplars fertilized at planting in the boreal forest of western Quebec. *Forest Ecology and Management,* 255**,** 2981-2989.

GUNN, J. S., GANZ, D. J. & KEETON, W. S. 2011. Biogenic vs. geologic carbon emissions and forest biomass energy production. *Global Change Biology Bioenergy,* 4**,** 239-242.

HANSEN, E. A. 1991. Energy plantations in north central United States - status of research and development plantations. *Energy Sources,* 13**,** 105-110.

HANSON, D. R. 2010. Timber resources on state forest lands in the Tanana Valley - Inventory update Draft. *In:* STATE OF ALASKA, D. O. N. R. (ed.). Division of Forestry Northern Region.

HEILMAN, P. E. & PEABODY JR, D. V. 1981. Effect of harvest cycle and spacing on productivity of black cottonwood in intensive culture. *Canadian Journal of Forest Research,* 11**,** 118-123.

HELLER, M. C., KEOLEIAN, G. A. & VOLK, T. A. 2003. Life cycle assessment of a willow bioenergy cropping system. *Biomass and Bioenergy,* 25**,** 147-165.

HOFMANN-SCHIELLE, C., JUG, A., MAKESCHIN, F. & REHFUESS, K. E. 1999. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. I. Site–growth relationships. *Forest Ecology and Management,* 121**,** 41-55.

HYTÖNEN, J., LUMME, I. & TÖRMÄLÄ, T. 1987. Comparison of methods for estimating willow biomass. *Biomass,* 14**,** 39-49.

ISEBRANDS, J. G. & KARNOSKY, D. F. 2001. Environmental Benefits of Poplar Culture. *In:* DICKMANN, D. I., ISEBRANDS, J.G.; ECKENWALDER, J.E.; RICHARDSON, J. (ed.) *Poplar Culture in North America. Ontario, Canada: NRC Research Press.*

JENKINS, J. C., CHOJNACKY, D. C., HEATH, L. S. & BIRDSEY, R. A. 2003. National scale biomass estimators for United States tree species. *Forest Science,* 49**,** 12-35.

JOHANSSON, B., BORJESSON, P., ERICSSON, K., NILSSON, L. J. & SVENNINGSSON, P. 2002. The use of biomass for energy in Sweden - critical factors and lessons learned. *Environmental and Energy System Studies.* Lund, Sweden: Lund University.

JOHANSSON, T. & KARACIC, A. 2011. Increment and biomass in hybrid poplar and some practical implications. *Biomass & Bioenergy,* 35**,** 1925-1934.

JOHNSON, E. 2009. Goodbye to carbon neutral: Getting biomass footprints right. *Environmental Impact Assessment Review,* 29**,** 165-168.

KAČÍK, F., ĎURKOVIČ, J. & KAČÍKOVÁ, D. 2012. Chemical profiles of wood components of poplar clones for their energy utilization. *Energies,* 5**,** 5243-5256.

KARACIC, A., VERWIJST, T. & WEIH, M. 2003. Above-ground woody biomass production of short-rotation *Populus* plantations on agricultural land in Sweden. *Scandinavian Journal of Forest Research,* 18**,** 427-437.

KEOLEIAN, G. A. & VOLK, T. A. 2005. Renewable energy from willow biomass crops: life cycle energy, environment and economic performance. *Critical Reviews in Plant Sciences,* 24**,** 385-406.

KETZLER, A. 2012. Personal Communication, City Manager - City of Tanana, Alaska.

KOPP, R. F., ABRAHAMSON, L. P., WHITE, E. H., BURNS, K. F. & NOWAK, C. A. 1997a. Cutting cycle and spacing effects on biomass production by a willow clone in New York. *Biomass and Bioenergy,* 12**,** 313-319.

KOPP, R. F., ABRAHAMSON, L. P., WHITE, E. H. & VOLK, T. A. 1997b. Willow Bioenergy Producer's Handbook. Syracuse, NY: State University of New York.

LANGHAMMER, B. O. & REP, A. 1967. Et 10-a˚ rig plantefelt av *Populus trichocarpa* (Hook.) i A˚ s. Zusammenfassung: Eine 10-ja¨hrige versuchsfla¨che von *Populus trichocarpa* (Hook.). *A˚ s Norw For Res Inst,* 23**,** 45-65.

LAUREYSENS, I., BOGAERT, J., BLUST, R. & CEULEMANS, R. 2004. Biomass production of 17 poplar clones in a short-rotation coppice culture on a waste disposal site and its relation to soil characteristics. *Forest Ecology and Management,* 187**,** 295-309.

LAUREYSENS, I., DERAEDT, W. & CEULEMANS, R. 2005a. Population dynamics in a 6-year-old coppice culture of poplar II. Size variability and one-sided competition of shoots and stools. *Forest Ecology and Management,* 218**,** 115-128.

LAUREYSENS, I., PELLIS, A., WILLEMS, J. & CEULEMANS, R. 2005b. Growth and production of a short rotation coppice culture of poplar. III. Second rotation results. *Biomass & Bioenergy,* 29**,** 10-21.

NETER, J., KUNTNER, M. H., NACHTSHEIM, C. J. & WASSERMAN, W. 1996. *Applied Linear Regression Models*, Richard D. Irwin, Inc. Chicago.

NORBY, R. J. & O'NEILL, E. G. 1991. Leaf area compensation and nutrient interactions in CO_2-enriched seedlings of yellow-poplar (*Liriodendron tulipıfera* L.). *New Phytologist,* 117**,** 515-528.

NORDH, N.-E. 2005. *Long Term Changes in Stand Structure and Biomass Production in Short Rotation Willow Coppice.* Ph.D, Swedish University of Agricultural Sciences.

OTT, R. A., LEE, M. A., PUTMAN, W. E., MASON, O. K., WORUM, G. T. & BURNS, D. N. 2011. Bank erosion and large woody debris recruitment along the Tanana River, Interior Alaska. *In:* ALASKA DEPARTMENT OF NATURAL RESOURCES DIVISION OF FORESTRY AND TANANA CHIEFS CONFERENCE, I. F. P. (ed.).

PEICHL, M., THEVATHASAN, N., GORDON, A. M., HUSS, J. & ABOHASSAN, R. A. 2006. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada. *Agroforestry Systems,* 66**,** 243-257.

PERSSON, A. 1973. Ett fo¨ rso¨k medsnabbva¨xande *Populus*-arter. (A trial with fast-growing *Populus* species) [In Swedish]. *Stockholm: Institutionen fo¨ r skogsproduktion, Skogsho¨gskolan,* 27**,** 1-34.

PROE, M. F., GRIFFITHS, J. H. & CRAIG, J. 2002. Effects of spacing, species and coppicing on leaf area, light interception and photosynthesis in short rotation forestry. *Biomass and Bioenergy,* 23**,** 315-326.

ROGERS, A., MCDONALD, K., MUEHLBAUER, M. F., HOFFMAN, A., KOENIG, K., NEWMAN, L., TAGHAVI, S. & VAN DER LELIE, D. 2012. Inoculation of hybrid poplar with the endophytic bacterium *Enterobacter sp* 638 increases biomass but does not impact leaf level physiology. *Global Change Biology Bioenergy,* 4**,** 364-370.

RYTTER, L. 2006. A management regime for hybrid aspen stands combining conventional forestry techniques with early biomass harvests to exploit their rapid early growth. *Forest Ecology and Management,* 236**,** 422-426.

RYTTER, L. & STENER, L. G. 2005. Productivity and thinning effects in hybrid aspen (*Populus tremula* L. x *P. tremuloides* Michx.) stands in southern Sweden. *Forestry,* 78**,** 285-295.

RYTTER, R. M. 2012. The potential of willow and poplar plantations as carbon sinks in Sweden. *Biomass & Bioenergy,* 36**,** 86-95.

SCARACIA-MUGNOZZA, G. E., CEULEMANS, R., HEILMAN, P. E., ISEBRANDS, J. G., STETTLER, R. F. & HINCKLEY, T. M. 1997. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. II. Biomass components and harvest index of hybrid and parental species clones. *Canadian Journal of Forest Research,* 27**,** 285-294.

SCHNABEL, W. E., MUNK, J., ABICHOU, T., BARNES, D., LEE, W. & PAPE, B. 2012. Assessing the performance of a cold region evapotranspiration landfill cover using lysimetry and electrical resistivity tomography. *International Journal of Phytoremediation,* 14**,** 61-75.

SCHULZE, E. D., KORNER, C. I., LAW, B. E., HABERL, H. & LUYSSAERT, S. 2012. Large-scale bioenergy from additional harvest of forest biomass is neither sustainable nor greenhouse gas neutral. *Global Change Biology Bioenergy,* 4**,** 611-616.

SIMS, R. E. H., HASTINGS, A., SCHLAMADINGER, B., TAYLOR, G. & SMITH, P. 2006. Energy crops: current status and future prospects. *Global Change Biology,* 12**,** 2054-2076.

SINGH, B. & BEHL, H. M. 1999. Energy flow, carbon and nitrogen cycling in *Populus deltoides* clones in north India. *Biomass and Bioenergy,* 17**,** 345-356.

SNOWDON, P. 1991. A ratio estimator for bias correctio in logarithmic regressions. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere,* 21**,** 720-724.

STANTURF, J. A., VAN OOSTEN, C., NETZER, D. A., COLEMAN, M. D. & PORTWOOD, C. J. 2001. Ecology and silviculture of poplar plantations. *In:* DICKMANN, D. I., ISEBRANDS, J. G., ECKENWALDER, J. E. & RICHARDSON, J. (eds.) *In: Poplar Culture in North America. Ontario, Canada: NRC Research Press.*

SWAMY, S. L., MISHRA, A. & PURI, S. 2006. Comparison of growth, biomass and nutrient distribution in five promising clones of *Populus deltoides* under an agrisilviculture system. *Bioresource Technology,* 97**,** 57-68.

TAHVANAINEN, L. 1996. Allometric relationships to estimate above-ground dry-mass and height in *Salix. Scandinavian Journal of Forest Research,* 11**,** 233-241.

TELENIUS, B. F. 1999. Stand growth of deciduous pioneer tree species on fertile agricultural land in southern Sweden. *Biomass and Bioenergy,* 16**,** 13-23.

TILMAN, D., HILL, J. & LEHMAN, C. 2006. Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science,* 314**,** 1598-1600.

TUSKAN, G. A. & RENSEMA, T. R. 1992. Clonal differences in biomass characteristics, coppice ability, and biomass prediction equations among four *Populus* clones grown in eastern North Dakota. *Canadian Journal of Forest Research,* 22**,** 348-354.

VERWIJST, T. & TELENIUS, B. 1999. Biomass estimation procedures in short rotation forestry. *Forest Ecology and Management,* 121**,** 137-146.

VOLK, T. A., ABRAHAMSON, L. P., NOWAK, C. A., L.B. , SMART, L. B., P.J. , THARAKAN, P. J. & WHITE, E. H. 2004a. Growing fuel: a sustainability assessment of willow biomass crops. *Frontier Ecology Environment,* 2**,** 411-418.

VOLK, T. A., ABRAHAMSON, L. P., NOWAK, C. A., L.B. , SMART, L. B., P.J. , THARAKAN, P. J. & WHITE, E. H. 2006. The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts agroforestry and phytoremediation. *Biomass and Bioenergy,* 30**,** 715-727.

VOLK, T. A., VERWIJST, T., THARAKAN, P. J., ABRAHAMSON, L. P. & WHITE, E. H. 2004b. Growing fuel: a sustainability assessment of willow biomass crops. *Frontiers in Ecology and the Environment,* 2**,** 411-418.

WITTMER, R. F. & IMMEL, M. J. 1976. A comparison of five tree species for intensive fiber production. *Forest Ecology and Management,* 1**,** 249-254.

WRIGHT, L., BOUNDY, B., PERLACK, B., DAVIS, S. & SAULSBURY, B. 2006. *Biomass Energy Data Book,* http://digitalcommons.unl.edu/usdoepub/4, US Department of Energy Publications.

YARIE, J., KANE, E. & MACK, M. 2007. Aboveground biomass equations for the trees of interior Alaska. Agricultural and Forestry Experimental Station Bulletin: School of Natural Resources and Agricultural Sciences, University of Alaska, Fairbanks.

YARIE, J. & MEAD, B. R. 1988. Twig and foliar biomass estimation equations for major plant species in the Tanana River basin of interior Alaska. Res. Prp. PNW-RP-401. U.S. Department of Agriculture, Forest Service: Pacific Northwest Research Station.

YARIE, J. & MEAD, D. 1982. Aboveground tree biomass on productive forest land in Alaska, RN PNW-298, US Department of Agriculture, Forest Service, Portland, OR.

ZABEK, L. M. & PRESCOTT, C. E. 2006. Biomass equations and carbon content of aboveground leafless biomass of hybrid poplar in Coastal British Columbia. *Forest Ecology and Management,* 223**,** 291-302.

ZALESNY, J. A., ZALESNY JR, R. S., COYLE, D. R. & HALL, R. B. 2007. Growth and biomass of *Populus* irrigated with landfill leachate. *Forest Ecology and Management,* 248**,** 143-152.

ZANCHI, G., PENA, N. & BIRD, N. 2012. Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *Global Change Biology Bioenergy,* 4**,** 761-772.

ZASADA, J., VIERECK, L. A., FOOTE, M. J., PARKENSON, R. H., WOLFF, J. O. & LANKFORD JR., L. A. 1981. Natural regeneration of balsam poplar following harvesting in the Susitna Valley, Alaska. *The Forestry Chronicle,* 57**,** 57-65.

ZIANIS, D. & MENCUCCINI, M. 2004. On simplifying allometric analyses of forest biomass. *Forest Ecology and Management,* 187**,** 311-332.