Resource assessment and analysis of aspen-dominated ecosystems in the Lake States

A DISSERTATION
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

Grant Michael Domke

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

Alan R. Ek, Anthony W. D'Amato

August 2010

Acknowledgements

I would like to thank my advisors, Alan Ek and Anthony D'Amato, for helping me realize my potential through guidance, support, and the many opportunities you have given me over the last several years. I would also like to thank the members of my graduate committee, Andrew David, Steven Katovich, and Michael Ostry, and colleague, Charles Blinn for their guidance, friendship, and support in all areas of my research and learning.

The work in this dissertation was made possible by funding from the University of Minnesota Department of Forest Resources, Minnesota Power, National Council for Air and Stream Improvement, Inc., Aspen/Larch Genetics Cooperative, and the Interagency Information Cooperative, and the McIntire-Stennis Cooperative Forest Research Program.

I would like to thank my family, particularly my parents, Todd and Vicki for their undying support in life and learning. Finally, this dissertation would not have been possible without the patience and steadfast support from my wife, Tracey. Thank you.

Table of Contents

Acknowledgements i

Table of Contents ii

List of Tables vi

List of Figures viii

Chapter 1 1

Introduction 1

1.1 Overview 2

Chapter 2 5

Aspen in the Lake States: a research review 5

2.1 Introduction 6

2.2 Resource status and trends 9

2.2.1 Forest type history 9

2.2.2 Usage, supply and demand 13

2.2.3 Growth and yield 20

2.3 Biology and ecology 22

2.3.1 Regeneration 22

2.3.2 Genetics and improvement 24

2.3.3 Soils and site productivity 29

2.3.4 Forest health 32

2.3.5 Wildlife habitat 37

2.4 Silviculture 40

2.5 Economics 48

2.6 Research Needs and Strategies 53
2.6.1 Resources status and trends 53
2.6.2 Biology and ecology 54
2.6.3 Silviculture 55
2.6.4 Economics 56

Chapter 3 58

Hybrid aspen response to shearing in Minnesota: implications for biomass production 58

3.1 Introduction 59
3.2 Methods 62
3.2.1 Site conditions and treatment history 62
3.2.2 Sampling methods 63
3.2.3 Data analysis 65
3.3 Results 65
3.3.1 Stem density 65
3.3.2 Tree characteristics 66
3.3.3 Volume and biomass production 68
3.4 Discussion 70
3.4.1 Stem density 70
3.4.2 Tree characteristics 72
3.4.3 Stand volume, biomass production, and carbon storage 74
3.4.4 Silvicultural methods for stand development 75
3.4.5 Harvesting considerations 76
3.5 Conclusion 77

Chapter 4 78

Model framework for the assessment of carbon flows associated with the procurement and utilization of harvest residues for energy 78

4.1 Introduction 79

4.2 Methods 81

4.2.1 Definitions 81

4.2.2 Study area 81

4.2.3 Data sources 82

4.2.4 Carbon flow model 87

4.2.5 Forest age class change model 87

4.3 Carbon sequestration 89

4.3.1 Decay emissions 92

4.3.2 Harvesting emissions 93

4.3.3 Transportation emissions 97

4.3.4 Carbon flow model assumptions 97

4.3.5 Trace gas assumptions 99

4.4 Results 100

4.4.1 Biomass availability 100

4.4.2 Carbon stocks 101

4.4.3 Carbon sequestration 101

4.4.4 Decay emissions 103

4.4.5 Harvesting and transport emissions 104

4.4.6 Carbon flow summary 105

4.5 Discussion 106

4.5.1 Carbon flows ... 106

4.5.2 Improvements in forest management and harvesting ... 110

4.5.3 Comparisons to fossil fuels ... 111

4.6 Conclusions ... 112

Chapter 5 ... 114

Model development for rapid estimation of forest-derived biomass availability ... 114

5.1 Introduction ... 115

5.2 Model development ... 117

5.2.1 User interface ... 117

5.2.2 Data inputs ... 118

5.2.3 Area change matrix ... 120

5.2.4 Biomass estimation ... 122

5.2.5 Model assumptions ... 123

5.3 Model applications ... 123

5.3.1 Assessment of carbon flows associated with the utilization of harvest residues for energy ... 123

5.3.2 Assessing forestation opportunities for carbon sequestration in Minnesota 124

5.3.3 2010 Outlook for Forest Biomass Availability in Minnesota ... 124

5.4 Discussion ... 125

Chapter 6 ... 127

Conclusion ... 127

Bibliography ... 131

List of Tables

Table 2.1 Area of timberland by state, FIA forest type group, and inventory period. Note that 2008 estimates are based on the annual inventory period from 2004-2008 whereas earlier estimates are based on periodic inventories. Values may not sum to total due to rounding. 11

Table 2.2 Area of aspen timberland by state, ownership, and age class for the 2004-2008 inventory period. 17

Table 2.3 Aspen timberland volume (cuft/ac) by age class, state, and inventory year..... 18

Table 2.4 Area of aspen timberland by state, site productivity class (cuft/ac/year), and inventory year. 19

Table 2.5 Silvicultural practices for aspen management in the Lake States (adapted from Cleland *et al.* 2003).[a] 43

Table 3.1 Description of study sites, sample sizes, and site activities. 63

Table 3.2 Pre-and post-shear stem density information for the five study sites. 66

Table 3.3. Descriptive statistics of the measured and calculated individual tree characteristics: tree height (m), diameter at breast height (dbh) (cm), and volume (dm^3) for grouped sites: Hybrid 3 (age seven) and Hybrid 2 (age eight) aspen saplings and suckers prior to shearing treatments, Hybrid 1 and Hybrid 3 (age ten) suckers post-shearing, and Native 1 and Native 2 (age ten) suckers post-shearing. 68

Table 4.1 Forest types by acres and stand age class for the project study area. 83

Table 4.2 Average biomass per acre (tonnes) by stand age class and forest type for the project study area. 84

Table 4.3 Estimated annual roundwood and residual biomass harvest targets for the study area based on the average statewide harvest levels by forest type over the last 5 years. 85

Table 4.4 Equipment productivity for harvesting sub-merchantable biomass less than 12.7 cm dbh (based on Sturos et al. 1983). 86

Table 4.5 Equipment productivity for harvesting logging residues – tops and limbs (based on Sturos et al. 1983). 86

Table 4.6 Proportion of the Minnesota statewide harvest volume within the study area used to define harvest targets (study area ODT). 89

Table 4.7 Annual carbon sequestration/acre (tonnes C) for the forest types in the study area calculated using FIA and COLE data and linear regression. 95

Table 4.8 Decay constants used to calculate the annual decomposition of extractable biomass within the study area. 96

Table 4.9 Estimated annual carbon stocks (CO_2) by forest type within the study area. . 102

Table 4.10 Estimated total carbon stocks (CO_2) by forest type within the study area. .. 102

Table 4.11 Estimated carbon (M tonnes CO_2) sequestered annually and over the 100-year planning period within the study area. 103

Table 4.12 Estimated carbon (M tonnes of CO2) emitted through decomposition annually and over the 100-year planning horizon from extractable biomass left on the harvest site for each forest type. 104

Table 4.13 Esimtated annual and cumulative (100-year) carbon (M tonnes of CO_2) emissions from harvesting and transport for each forest type within the study area. 105

Table 4.14 Estimated annual carbon stock changes with and without the proposed bioenergy facility. Extractable residue removed values have been adjusted based on total plant capacity (ca. 89 percent of total extractable residue available). 108

Table 4.15 Estimated cumulative (100-years) carbon stock changes with and without theproposed bioenergy facility. Extractable residue removed values have been adjusted based on total plant capacity (ca. 89 percent of total extractable residue available). 109

Table 5.1 Forest type area (acres) by age class for Minnesota FIA Survey Units 1-3[1] . . 119

Table 5.2 Harvest level targets by forest type based on the 10-year average statewide harvest levels in Minnesota (Becker et al. 2010a). 120

Table 5.3 Example of the age class change matrix within each forest type sheet. 121

List of Figures

Figure 2.1 Aspen forest type and total timberland area (all forest types) by ownership class and state for the inventory period 2004-2008. 14

Figure 2.2 Aspen timberland by state and inventory period (Inventory 1 = 1980 (MI), 1977 (MN), and 1983 (WI), Inventory 2 = 1993 (MI), 1990 (MN), and 1996 (WI), and Inventory 3 = 2008. 15

Figure 2.3 Percent of all live aspen volume within forest type groups in the Lake States for the 2004-2008 inventory period. 18

Figure 2.4 Net aspen forest type volume (cuft/acre) by age class and state for the 2004-2008 inventory period. 21

Figure 2.5 Comparison of aspen timberland volume with a gross volume equation developed by Walters and Ek (1993) for specific site indices for the 2004-2008 inventory period in the Lake States. 22

Figure 2.6 Area of aspen timberland damaged by biotic and abiotic agencies during the 2004-2008 inventory period in the Lake States. 34

Figure 2.7 Historical stumpage prices for aspen pulpwood in the Lake States. 50

Figure 3.1 Estimated total stand volume (m^3/ha) from 0.15 m stump to tip of all trees ≥ 0.30 m tall for post-shear ten-year-old native and hybrid aspen stands. Native 1 and 2 (site index = 21.6), Hybrid 1 (site index = 24.4), and Hybrid 3 (site index = 21.3). 69

Figure 3.2 Estimated total aboveground biomass (oven dry tonnes/ha) for trees 2.5 cm dbh and larger for post-shear ten-year-old native and hybrid aspen stands. Native 1 and 2 (site index = 21.6), Hybrid 1 (site index = 24.4), and Hybrid 3 (site index = 21.3). 70

Figure 4.1 Sensitivity analysis using COLE data and linear regression to determine the age at which carbon sequestration begins to change for the aspen forest type......... 90

Figure 4.2 Regression analysis (empirical) used to estimate annual sequestration/acres for stands < 40-years for the aspen forest type within the study area. 94

Figure 4.3 Regression analysis using COLE—generated carbon stocks to calculate the annual carbon sequesztration/ acre for stands < 40 years of age for the aspen forest type in Minnesota. 94

Figure 4.4 Regression analysis using COLE - generated carbon stocks to calculate the annual carbon sequestration/acre for stands > 40 years of age for the aspen forest type in Minnesota. 95

Figure 4.5 Estimated carbon inputs and outputs (M tonnes of CO_2/MWh) over the 100-year planning period for the proposed bioenergy facility. 110

Chapter 1

Introduction

1.1 Overview

The work presented in this dissertation began not with a literature review, but with a review of land survey records and forest inventory information dating back to the turn of the last century. The goal of the review was to characterize changes in the aspen forest type in the Lake States (Michigan, Minnesota, and Wisconsin). The data showed a transformation of the forested landscape in the region from predominately mature, long-lived, shade tolerant species and forest types, to young, short-lived, shade-intolerant forests, dominated by a so-called "weed tree" (mainly *Populus trembuloides* Michx., and to a lesser extent, *P. grandidentata* Michx. and *P. balsamifera* L.). Early research by Kittredge and Gevorkiantz (1929) and the subsequent (University of Minnesota) dissertation by Kittredge (1938) helped tell the story of the massive human-induced forest type change. Since the recorded peak of aspen forest type acreage in the 1930s, it has steadily declined in Michigan and Wisconsin and, to a lesser extent, in Minnesota (Domke et al. 2008b). Nevertheless, aspen remains the most dominant forest type in the Lake States and continues to be the most utilized group of species in the region.

The goal of this dissertation is to contribute to the existing literature on aspen forest type trends and to present a methodology for estimating biomass availability and carbon flows associated with the extraction, transport, and utilization of woody biomass for energy. The chapters in this body of work focus on four main areas: 1) status and trends from aspen-dominated ecosystems in the Lake States, 2) analysis of biomass production potential in native and hybrid aspen communities, 3) estimation of carbon flows associated with the procurement and utilization of harvest residues for energy, and

4) development of a spreadsheet-based model for rapid estimation of biomass availability. The paragraphs below describe the four main dissertation chapters.

Chapter 2 has been published by the National Council for Air and Stream Improvement, Inc. as Technical Bulletin No. 955. In this chapter, Domke et al. (2008b) describe the status and trends of aspen research in the Lake States (including its economic and environmental contributions) and characterize current research on management, productivity, and environmental considerations for the species. The report also suggests strategies to help meet industry needs for information and technology transfer and identifies research gaps and areas for potential collaboration.

Chapter 3 is in press at the *Northern Journal of Applied Forestry*. In this chapter, Domke et al. (In press) investigate the production potential of woody biomass feedstocks from native and hybrid aspen stands following shearing. This study documents more than 20 years of individual tree and yield measurements in hybrid aspen (*Populus tremuloides* Mich. x *P. tremula* L.) stands in north central Minnesota. Specifically, tree- and stand-level responses are described in terms of sucker density, early diameter and height characteristics, volume, and biomass production. Overall, shearing treatments increased the density of hybrid aspen stems relative to pre-shear densities at the same age. In addition, average stem diameter and volume as well as stand-level biomass were considerably greater in hybrid aspen stands relative to similarly aged native aspen stands also established via shearing treatment. These findings illustrate that coppice systems using hybrid aspen provide great potential to rapidly produce biomass feedstocks, with little management investment.

Chapter 4 was originally developed as a technical report for an energy utility in northern Minnesota and was published internally as a Department of Forest Resources Staff Paper No. 198. The report (Domke et al. 2008a) has since been adapted for submission to *Biomass and Bioenergy* (Domke et al. In prep. 1). This chapter describes the development of a model framework for the estimation of biomass availability and carbon flows associated with the extraction, transport, and utilization of harvest residues for energy. While all commercially important forest types are presented in this analysis, the aspen type was used to develop and initially test the model outputs. Study results suggest there are carbon costs associated with the utilization of harvest residues for energy production but that they are markedly lower than direct CO_2 emissions reported for fossil fuels (i.e., exclusive of extraction, refinement, and transport emissions).

Chapter 5 describes the development of a spreadsheet-based model designed to estimate biomass availability over multiple spatial and temporal scales. The model was originally developed as part of the work described in chapter 4 (Domke et al. 2008a) and has since been refined and used in a variety of biomass- and carbon-related projects. This chapter has been formatted for submission to the *Northern Journal of Applied Forestry* (Domke et al. In prep. 2). The final chapter presents a general summary, including potential directions for future research.

Chapter 2

Aspen in the Lake States: a research review

Aspen species are critical components of forests in the Lake States, with important economic and environmental contributions to the region. There is a modest, ongoing investment in aspen research, but the research is fragmented and not always closely linked to industry information needs. Closer communication and collaboration between the forest research scientists and industrial forest managers is needed to ensure that limited research funding is allocated to priority topics and that research outputs are relevant to industry managers and can be used to develop strategies to best utilize and sustain this resource. This is particularly important given the changing nature of the forest products industry in the region and for larger-scale issues related to fiber supply, global competitiveness, and the role of forests in carbon sequestration and bioenergy production. This research assessment summarizes the status and trends of aspen in the Lake States, including its economic and environmental contributions, and characterizes current research on management, productivity, and environmental considerations for aspen. It also suggests strategies to help meet industry needs for information and technology transfer and identifies research gaps and areas for potential collaboration.

2.1 Introduction

Quaking and bigtooth aspen (*Populus tremuloides* Michx. and *P. grandidentata* Michx.) and balsam poplar (*P. balsamifera* L.) are classic examples of early successional, pioneer tree species (Perala 1990). They are disturbance-dependent, fast growing, short lived, and require high light environments for establishment and rapid growth (Brinkman and Roe 1975, Perala 1990, Alban *et al.* 1991, Sheppard 2001). Despite sharing many of the same life history traits and coexisting throughout the Great Lakes region, their overall geographic distributions differ (Little 1971, Burns and Honkala 1991). Quaking aspen is the most widely distributed tree species in North America with a transcontinental range (Little 1971, Burns and Honkala 1991) extending from the tree line in northwestern Alaska south to the mountains of Mexico. Balsam poplar also has a transcontinental range, but is restricted to Canada and Alaska and the northernmost parts of the eastern U.S. (Burns and Honkala 1991). Bigtooth aspen has the smallest native range of the three species, found throughout the Northeast and North Central U.S. and adjacent Canada (Burns and Honkala 1991).

The aspens and balsam poplar have important economic value and provide many ecosystem services across their respective ranges. They provide erosion control, groundwater recharge, habitat and forage for wildlife, insects, and pathogens, and aesthetic value (Alban 1991, Burns and Honkala 1991, Potter-Witter and Ramm 1992, David et al. 2001). Their economic importance has evolved over the last one hundred years, particularly in the North Central region (Minnesota, Wisconsin, and Michigan) of the United States where turn-of-the-century logging and fires created ideal conditions for disturbance-dependent species (Graham et al. 1963, Cleland et al. 2003). The aspens and balsam poplar (hereafter referred to collectively as aspen) have gone from weed tree to one of the most highly sought after commercial species in the Lake States (Einspahr and Wykoff 1990, Alban et al. 1991, Balatinecz and Kretschmann 2001, David et al. 2001, Piva 2006). Today, aspen is a premier pulp and paper species and is used heavily in engineered wood products in the region (Burns and Honkala 1991, Piva 2006). The demand for these wood products, along with fire suppression, natural succession, premature dieback, land conversion, forest management practices, and pests and pathogens, has led to declines in these species across North America and particularly the Lake States (Cleland et al. 2003, Frey et al. 2004). These declines, along with the importance of maintaining ecological function in managed forests, have led to changes in how aspen is managed across the region. Traditional aspen silviculture has been augmented by silvicultural systems and associated practices which increase biodiversity, capture early mortality, and improve tree growth and form (David et al. 2001, Cleland et al. 2003, Ostry et al. 2004).

Over the last few decades, several reviews have documented and described the biology, ecology, economics and silviculture of aspen throughout the United States and Canada (Perala 1977, DeByle and Winokur 1985, Perala 1990, Peterson and Peterson 1992, David et al. 2001, Cleland et al. 2003, Frey et al. 2004). However, in the last decade, new markets and technologies have emerged, mill expansions and closures have changed fiber demand, total aspen acreage has continued to decline, and ecosystem management concepts have evolved to shape how these forests are managed, particularly on public lands.

This chapter describes the current status and knowledge of aspen in the Lake States and reviews the literature, highlighting recent findings and identifying critical gaps in our understanding of the species across the region. It also suggests strategies for linking research and emerging technologies to management.

2.2 Resource status and trends

2.2.1 Forest type history

Prior to European settlement, the aspens played an important, though minor, role in the forests of the Great Lakes region (Finley 1976, Comer et al. 1995, Almendinger 1997). Land survey information from the General Land Office in each of the three Lake States has been used to reconstruct pre-settlement forestland conditions (Finley 1976, Comer et al. 1995, Almendinger 1997). In northern Minnesota, an estimated 30 percent of the forest was composed of mixed conifer-aspen, aspen-birch, and aspen-oak. In northern Michigan and Wisconsin, aspen was a much smaller component of pre-settlement forests with approximately 300,000 acres in each state (Comer et al. 1995, Finley 1976).

Beginning around 1850 in central Michigan, settlers began clearing forestland to make way for farms and homesteads. By the 1930s, most of the virgin timber in the Lake States had been removed. During the 80-year cutover period, wildfires burned throughout the region, creating ecologically ideal conditions for aspen by reducing tree competition, creating an optimal seedbed, and stimulating vegetative reproduction (Graham et al. 1963, Haines and Sando 1969, Cleland et al. 2003). The result was a massive forest type conversion across the Lake States (Cleland et al. 2003, Friedman and Reich 2005).

Today, aspen/birch and the maple/beech/birch forest types are the two most prolific groups in the North Central states, occupying 12.6 and 10.4 million acres of timberland respectively (Table 2.1). Note all estimates in this chapter are based on USDA Forest

Service Forest Inventory and Analysis (FIA) inventories corresponding to the following periods in each state: Michigan 2004-2008 (annual), 1993 (periodic), 1980 (periodic); Minnesota 2004-2008 (annual), 1990 (periodic), 1977 (periodic), and Wisconsin 2004-2008 (annual), 1996 (periodic), 1983 (periodic). Minnesota has the largest proportion of that total aspen/birch timberland with more than 6 million acres (Table 2.1). Michigan and Wisconsin each have more than 3 million acres of aspen/birch timberland despite being dominated by the maple/beech/birch forest type (Table 2.1).

Following the extensive cutover at the turn of the last century, aspen was considered a useless weed (Holcomb and Jones 1938, Spencer and Thorne 1972, Graham et al. 1963, Balatinecz and Kretschmann 2001, Stone 2001). As the supply of more favorable timber species diminished and aspen stands reached merchantable size, several industries began using it (Holcomb and Jones 1938).

It was realized that the wood of this early successional, disturbance-dependent species could be pulped and was well suited for a variety of other forest products (Holcomb and Jones 1938, Lamb 1967, Einspahr and Wyckoff 1990, Balatinecz and Kretschmann 2001).

Table 2.1 Area of timberland by state, FIA forest type group, and inventory period. Note that 2008 estimates are based on the annual inventory period from 2004-2008 whereas earlier estimates are based on periodic inventories. Values may not sum to total due to rounding.

	Michigan			**Minnesota**			**Wisconsin**		
Forest Type Group	**1980**	**1993**	**2008**	**1977**	**1990**	**2008**	**1986**	**1996**	**2008**
White/red/jack pine	1,651,699	1,862,769	1,874,122	765,476	891,119	843,603	1,248,481	1,168,411	1,495,207
Spruce/fir	2,583,178	2,673,282	2,522,196	2,957,620	3,555,406	3,443,485	1,347,641	1,342,348	1,400,527
Oak/pine	-	-	572,957	-	-	254,783	-	-	609,491
Oak/hickory	1,764,459	1,985,924	3,100,421	928,560	1,166,615	1,997,739	2,858,904	2,884,732	4,150,491
Elm/ash/cottonwood	1,421,730	1,625,452	1,940,842	1,006,780	1,290,460	1,440,414	1,240,598	1,528,456	1,658,644
Maple/beech/birch	6,227,820	7,160,141	5,559,857	1,205,737	1,392,990	1,128,034	4,002,318	5,299,745	3,685,981
Aspen/birch	3,651,772	3,161,781	3,209,877	6,709,382	6,317,639	6,065,328	3,904,010	3,407,638	3,168,977
Other [1]	104,764	114,932	296,495	3,800	6,000	169,559	2,200	12,617	118,484
Nonstock	86,340	38,657	159,767	58,497	104,188	252,462	160,381	56,694	152,368
Total	17,492,921	18,615,900	18,807,016	13,613,100	14,723,200	14,988,709	14,759,400	15,700,884	15,886,555

[1] Other forest type group includes all types which occupy > 1 million acres across the three states: Other eastern softwoods group, Douglas-fir group, Fir/spruce/mountain hemlock group, Exotic softwoods group, Oak/gun/cypress group, Other hardwoods group, and Exotic hardwoods group.

The level of aspen pulpwood production across the region has increased substantially over the last 40 years and the aspens are now the dominant species harvested for pulpwood in the Lakes States, accounting for 41 percent of the 9.8 million cords harvested in 2004 (Piva 2006).

Since the recorded peak of the aspen/birch acreage in the 1930s, this forest type has declined in each of the three Lake States (Cleland et al. 2003). In Michigan and Wisconsin, acreage declined more than 36 percent from 1935 to 2004. The aspen/birch acreage declined by 6 percent over the same 69-year period in Minnesota (Cleland et al. 2003). These trends continue across the Lake States, although the declines have slowed over the last three decades (Table 2.1). Today, aspen/birch remains one of the two most dominant forest types, representing more than 24 percent of the 51 million acres of timberland in the region (Table 2.1). Only the maple/beech/birch forest type compares across the Lake States, representing approximately 20 percent of the region's timberland (Table 2.1).

Ownership patterns are important to understanding management options. In the Lake States, nearly 61 percent of the 51 million acres of timberland are privately owned with approximately 52 percent of the aspen timberland in private ownership (Figure 2.1). Since most of that is in non-industrial private forest (NIPF) ownership, such landowners are clearly crucial to aspen availability in the future. Public ownership is also important across the region and has evolved somewhat differently in each of the Lake States (Cleland et al. 2003). Minnesota's public lands are, in descending order of magnitude, state, local (county and municipal), and federal for both aspen and total timberlands (Figure 2.1). Wisconsin's public timberlands are primarily local (county and municipal), followed by federal and state lands (Figure 2.1). In Michigan, state and federal lands are the principal public ownerships, with a small number of acres in local forests (Figure 2.1). Additionally, most of these public timberlands are in the northern portions of the respective states.

2.2.2 Usage, supply and demand

Aspen is used for a wide variety of products (Lamb 1967, Einspahr and Wyckoff 1990, Balatinecz and Kretschmann 2001). Its light weight and color, as well as the fiber length, make it a desirable paper species because it can be pulped by most of the commercially important processes (Lamb 1967, Einspahr and Wyckoff 1990, Balatinecz and Kretschmann 2001). It is also well suited for use in building products such as hardboard, insulation board, particle board, and structural flake board (waferboard and oriented strand board) (Einspahr and Wyckoff 1990, Balatinecz and Kretschmann 2001). In addition, aspen wood is being used in paneling, matches, chop sticks, toys, core stock, containers, pallets, framing lumber, and interior trim (Lamb 1967, Einspahr and Wyckoff 1990, Balatinecz and Kretschmann 2001).

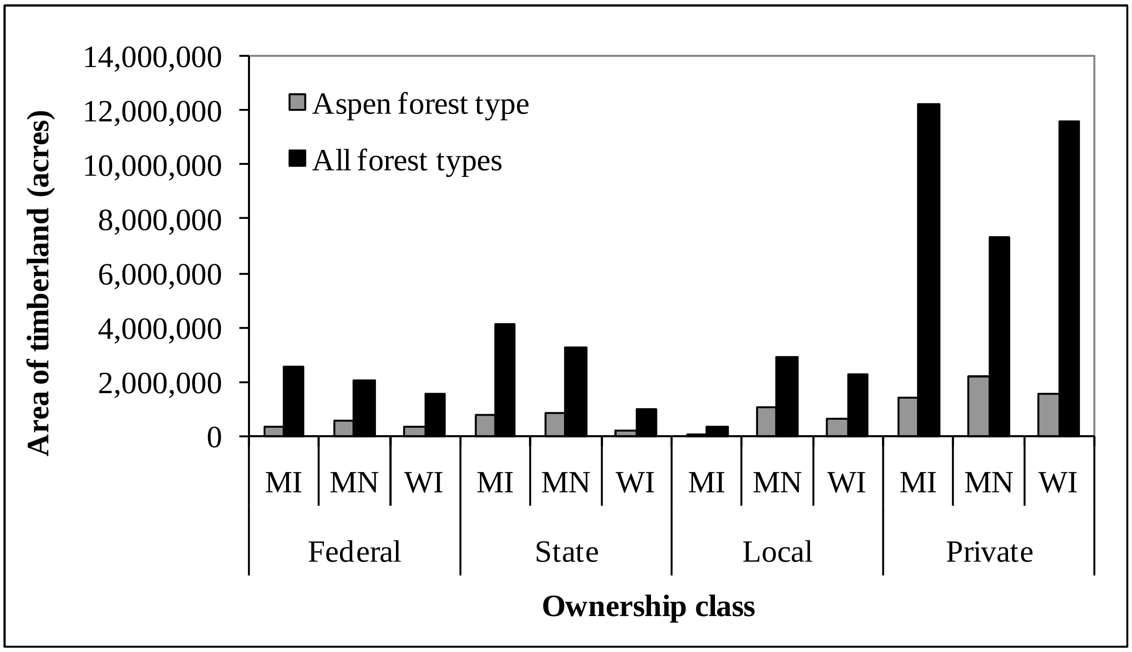

Figure 2.1 Aspen forest type and total timberland area (all forest types) by ownership class and state for the inventory period 2004-2008.

Aspen has long been used for fuelwood locally. That market has potential for considerable expansion with reemerging interest in biomass energy and new technologies for harvesting such as portable chipping and grinding equipment that can utilize small sized trees and residual material (Balatinecz and Kretschmann 2001). In addition, new technologies for converting wood to liquid fuels may lead to new value-added opportunities. Many forest products manufacturing facilities are already highly self-sufficient in terms of energy and are exploring options for increasing biomass energy production for internal use and/or sales to others. Increasing demand for biomass energy could affect competition for aspen and other wood resources.

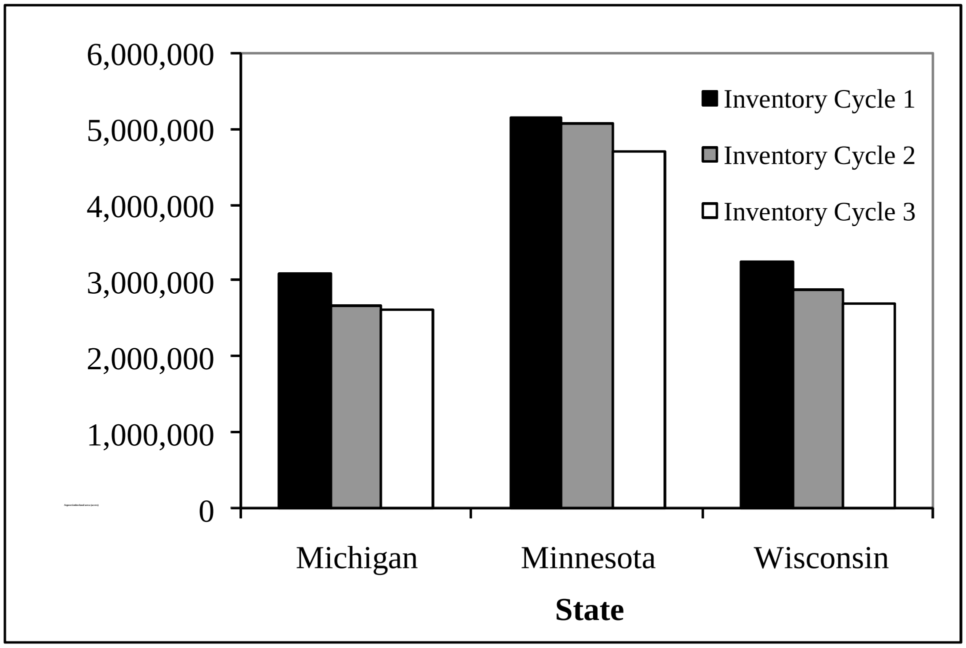

Figure 2.2 Aspen timberland by state and inventory period (Inventory 1 = 1980 (MI), 1977 (MN), and 1983 (WI), Inventory 2 = 1993 (MI), 1990 (MN), and 1996 (WI), and Inventory 3 = 2008.

Trends in aspen timberland acreage over the last three decades are summarized by state in Figure 2.2. Declines are evident in all three states. These changes are likely the result of natural succession and forestry practices that favor other species, e.g., favoring longer lived hardwoods by thinnings that remove aspen and leave hardwoods; or clearcutting and leaving hardwood residuals that shade and otherwise inhibit the regeneration of aspen. A role for natural succession is suggested by the fact that substantial areas of aspen timberland are in older age classes (Table 2.2). However, any interpretation is partly speculation as there has been no comprehensive analysis of factors that are leading to the decline of aspen acreage.

Aspen net volume per acre on timberland by age class is shown in Table 2.3. Net cubic foot volumes per acre vary substantially by state and inventory period which may suggest differences in site classes or levels of species composition. The net volume per acre steadily increases in each state and inventory period until approximately age 70 and thereafter fluctuates (Table 2.3). This suggests that extended rotations are unlikely to improve yields on some sites and that mortality and declining tree quality impact net yield accumulation for long rotation ages. However, the FIA aspen forest type definition is very broad (from 100 to as low as low as 30 percent aspen); thus, there is reason to investigate potential effects further, perhaps by species composition, site quality and stand treatment history. Yet stand treatment history impacts should be modest, as there has been minimal thinning or other intermediate treatments applied to aspen to date.

Table 2.4 indicates changes in the aspen forest type acreage by site productivity class over the last three inventory periods. The loss of aspen acreage is occurring on the moderately productive sites. This may be due to natural succession with aging and/or conversion following harvesting. Conversely, aspen appears to be increasing in the low productivity areas. This may also be due to natural succession, where previously abandoned sites (e.g., fields or mines) are now dominated by aspen. It may also be due to active aspen management on public lands which have historically been considered the low productivity areas that settlers did not want (Shands and Healy 1977, Cleland et al. 2003).

Table 2.2 Area of aspen timberland by state, ownership, and age class for the 2004-2008 inventory period.

Age class	Michigan				Minnesota				Wisconsin			
	Federal	**State**	**Local**	**Private**	**Federal**	**State**	**Local**	**Private**	**Federal**	**State**	**Local**	**Private**
0-10	8,114	86,758	5,155	132,257	63,251	187,362	182,045	348,896	23,299	34,861	108,776	242,687
11-20	42,248	137,366	7,754	132,259	98,121	133,725	176,217	294,866	35,780	34,835	118,679	208,127
21-30	52,825	99,119	568	196,873	70,191	100,390	152,931	310,891	61,049	31,321	102,748	208,107
31-40	55,745	140,749	6,358	214,112	73,257	80,047	97,688	266,948	48,050	29,957	114,153	253,514
41-50	54,626	101,563	10,061	256,515	49,355	125,349	124,337	289,525	62,525	31,800	62,192	251,298
51-60	59,822	77,762	5,613	199,897	77,211	94,425	109,252	273,246	34,149	29,722	24,502	206,097
61-70	41,572	60,899	6,730	157,447	85,131	81,492	142,227	224,234	24,097	6,208	33,247	135,287
71-80	41,727	18,269	5,022	96,728	33,204	38,195	72,766	126,684	19,993	11,585	10,789	52,263
81-90	7,909	18,499	2,289	45,831	25,894	5,297	14,961	32,987	4,425	5,596	-	23,944
91-100	2,257	1,635	-	14,600	14,552	-	6,137	747	1,402	2,106	-	792
100+	-	10,351	-	6,582	2,902	4,651	3,192	12,025	-	-	-	2,293
Total	366,845	752,970	49,550	1,453,101	593,069	850,933	1,081,753	2,181,049	314,769	217,991	575,086	1,584,409

Table 2.3 Aspen timberland volume (cuft/ac) by age class, state, and inventory year.

Age class	Michigan			Minnesota			Wisconsin		
	1980	**1993**	**2008**	**1977**	**1990**	**2008**	**1983**	**1996**	**2008**
0-10	947	1,604	606	336	1,320	482	1,065	1,754	602
11-20	675	922	791	426	653	544	773	1,183	623
21-30	916	1,209	767	662	904	584	1,089	1,176	720
31-40	2,289	1,511	1,165	1,128	1,382	807	1,805	1,626	1,047
41-50	3,673	2,792	1,377	1,367	1,795	1,170	2,869	2,461	1,216
51-60	3,930	3,422	1,760	1,472	2,071	1,268	2,518	2,605	1,628
61-70	2,881	3,409	1,870	1,544	2,205	1,608	1,871	2,123	1,616
71-80	2,653	3,093	2,153	1,736	2,112	1,708	1,720	1,945	2,233
81-90	2,375	3,079	2,264	1,833	2,202	1,660	1,866	1,969	2,313
91-100	1,886	2,492	1,871	2,059	2,406	2,030	1,994	2,802	1,692
100+	2,318	2,642	3,012	1,755	2,479	1,961	-	2,634	1,011

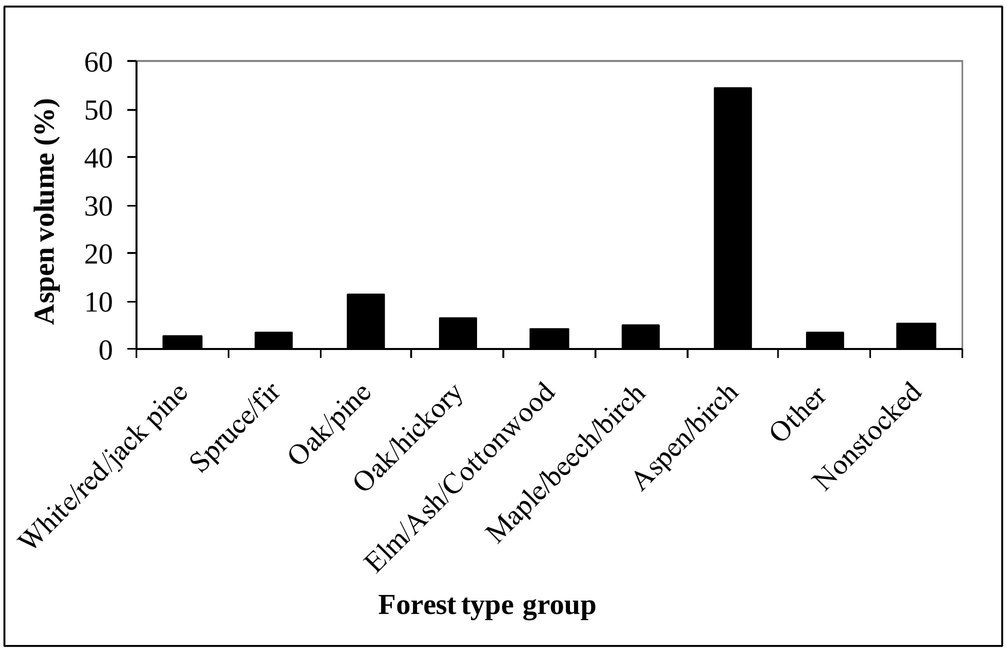

Figure 2.3 Percent of all live aspen volume within forest type groups in the Lake States for the 2004-2008 inventory period.

Table 2.4 Area of aspen timberland by state, site productivity class (cuft/ac/year), and inventory year.

Site Productivity Class	Michigan			Minnesota			Wisconsin		
	1980	**1993**	**2008**	**1977**	**1990**	**2008**	**1983**	**1996**	**2008**
20-49	437,800	275,855	517,781	766,465	553,728	974,961	347,867	204,562	331,157
50-84	1,252,056	1,178,454	1,131,989	2,707,801	2,609,771	2,423,346	1,548,287	1,273,168	1,094,157
85-119	1,245,994	1,053,485	848,182	1,573,335	1,831,157	1,227,020	1,293,822	1,218,853	1,109,222
120-164	134,676	150,224	104,260	98,899	59,401	68,329	71,291	156,224	134,831
165-224	18,465	22,502	16,511	11,198	4,000	15,914	-	32,275	22,891
225+	-	-	3,742	-	-	-	-	-	-
Total	3,088,991	2,680,520	2,622,465	5,157,698	5,058,057	4,709,570	3,261,267	2,885,082	2,692,258

While the interest here is focused on the aspen forest type, it is also important from a utilization standpoint to identify the other forest types that include substantial aspen volume. Figure 2.3 indicates the percent aspen timberland volume by forest type and describes the species that occur with aspen and the volume of aspen within other forest types. Clearly all of the other major forest types are important sources of aspen.

2.2.3 Growth and yield

Inspection of the empirical yield compilation shown in Figure 2.4 shows conventional yields (net volume of trees > 4.95 inches Dbh to a 4 inch top diameter outside bark (dob)) reaching approximately 1500 cubic feet per acre at age 50 and slightly higher at age 60. This suggests mean annual increment for most stands peaks at approximately 50 years. However, this is an FIA average yield and stands on better than average sites may perform better at either younger or older rotation ages. Walters and Ek (1993) modeled FIA data from Minnesota. Their results suggest that yields can be much higher on better than average sites (Figure 2.5). Additionally, plantation data suggests potential yields under intensive culture on the order of those achieved for short rotation hybrid poplars (Andrew J. David personal communication). Given that FIA data for aspen includes hundreds of plots measured on several occasions, it would be instructive to explore that data for possible trends in aspen stand yields with respect to site conditions, location, disturbance history, and other stand characteristics. Ecological classification systems may also help identify trends; however, few such systems have been rigorously examined with respect to their linkages to health and productivity.

Improvements in naturally regenerated aspen stand yields with early (precommercial) and/or commercial thinning are also of interest. Studies by Graham et al. (1963), Sorenson (1968), and Perala (1978) suggest that aspen, like many species, will respond well to early thinning at less than 10 to 20 years of age. Those studies also consider the concept of thinning early, light, and often to improve overall rotation yields and product mix. However, those studies have not been fully replicated, if at all. In fact, early and commercial thinning have been demonstrated as physically feasible from an equipment and operational aspect, but growth response data from re-measurements of those studies remains in short supply.

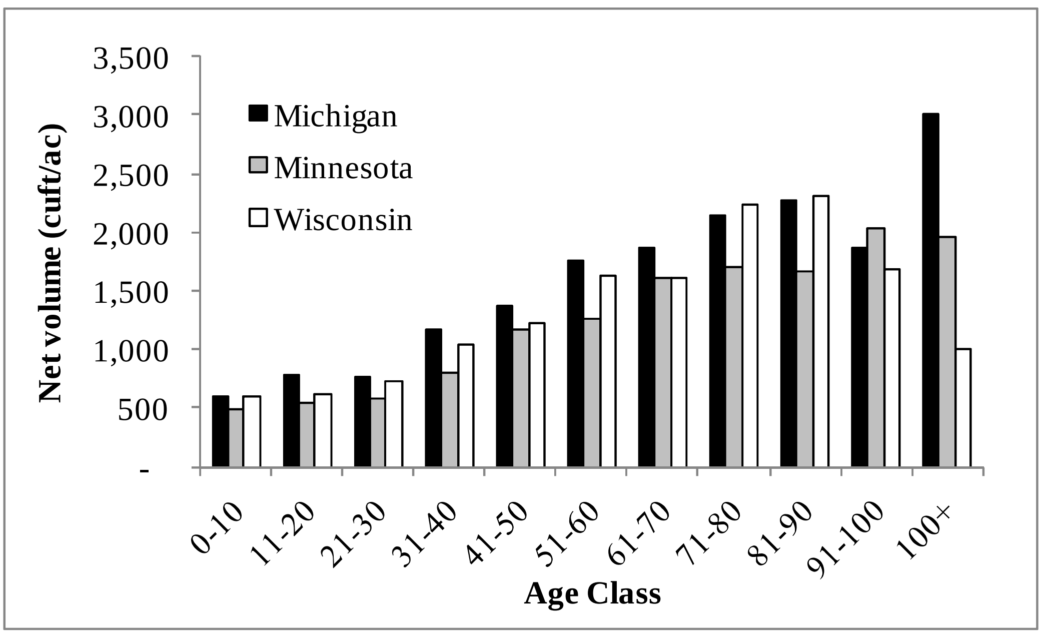

Figure 2.4 Net aspen forest type volume (cuft/acre) by age class and state for the 2004-2008 inventory period.

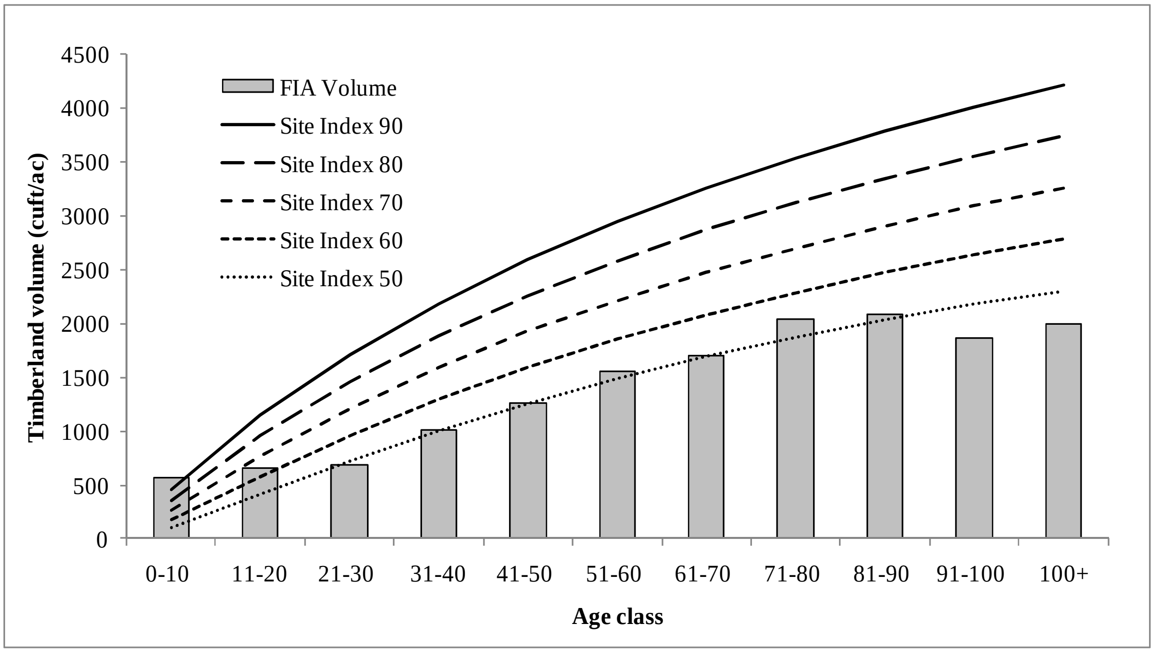

Figure 2.5 Comparison of aspen timberland volume with a gross volume equation developed by Walters and Ek (1993) for specific site indices for the 2004-2008 inventory period in the Lake States.

2.3 Biology and ecology

2.3.1 Regeneration

Aspen is a prolific seed producer and can begin flowering as early as 10 years of age (Maini 1968, Perala 1990). Once sexually mature, aspen produces good seed crops approximately every 5 years (Perala and Russell 1983, Perala 1990). The light, wind-dispersed seed has a germinative capacity of more than 95% under favorable conditions and typically lasts between 2 to 4 weeks (Maini 1968, Schopmeyer 1974, Perala 1990). Despite high seed viability and regularly abundant seed crops, aspen rarely regenerates sexually (Perala 1990, Peterson and Peterson 1992). This is largely due to a lack of soil moisture during seed dispersal, unfavorable soil temperature and soil chemistry, and the presence of fungal pathogens during the short germination period (Perala 1990, Peterson and Peterson 1992).

Most aspen regeneration comes from adventitious shoots or suckers that arise along its lateral root system (Farmer Jr. 1962, Steneker 1974, Perala 1977, Heeney et al. 1980, Perala 1990, Frey et al. 2003) following large-scale, stand replacing disturbances. Aspen is also capable of producing sprouts from its root collar and stump. Reproduction from these structures, however, is not common (DeByle and Winokur 1985). Where aspen is already present in a stand, suckering is the primary mode of regeneration with success dependent on growth hormones (Farmer Jr. 1962, Steneker 1974), root carbohydrate stores (Scheir and Zasada 1973), root size (Kemperman 1977), clonal variation (Maini 1967), soil temperature, root depth, soil moisture (Maini and Horton 1964), soil compaction, previous stand age, herbivory, and plant competition (David et al. 2001). Following natural stand-replacing disturbances and clearcutting, sucker densities of 20,000 to 30,000 stems per acre are not uncommon (DeByle and Winokur 1985, Perala 1990, Peterson and Peterson 1992). The number of aspen suckers quickly declines as clumps self-thin and, by the tenth year after disturbance, most clumps have been reduced to a single ramet (DeByle and Winokur 1985, Peterson and Peterson 1992). The result of this rapid self-thinning is clones of a few to several hundred stems extending from 1 to 5 acres (Peterson and Peterson 1992). Inter and intraclonal competition and mortality continue throughout the life of the stand (Peterson and Peterson 1992).

2.3.2 Genetics and improvement

In general, population genetics theory suggests that genetic variation increases with species environmental variation, population size, and range. It is not surprising then that both aspens and balsam poplar are genetically diverse tree species (Barnes 1966, Burns and Honkala 1991, Mitton and Grant 1996, Ostry et al. 1989, David et al. 2001, Madritch et al. 2006). With separate male and female trees, wind pollination ensures large levels of genetic diversity at the population level (Burns and Honkala 1991, David et al. 2001). Recent work by Madritch and Hunter (2002) and Madritch et al. (2006) suggests that loss of genetic variation within populations can influence community and ecosystem level processes such as litter decomposition and nutrient cycling. Within seedling-derived aspen populations, the greatest loss of genotypes and genetic variation occurs during the stand initiation phase when density-dependent mortality is at its peak (David et al. 2001). New genes enter populations from other populations via seed migration during seedling establishment and from pollen flow during flowering (David et al. 2001).

In clonally derived sucker stands, aspen genotypes are typically conserved on the site following disturbance so long as sucker production and growth are sustained from one generation to the next and the overall area of sucker production is maintained (David et al. 2001). However, the actual loss in genotypes, if any, associated with a disturbance event is unknown and is probably more closely related to intraspecific competition, an individual genotypes' propensity to sucker (Farmer Jr. 1962, Maini 1967, Steneker 1972) and soil conditions (Bates et al. 1998) than the actual disturbance event itself.

Based on the life history traits, natural levels of genetic variation, and geographic range of quaking aspen, the potential for improving any trait is similar to that of most conifers. For volume, that translates into an increase of approximately 15 to 22 percent per generation, but there are no native aspen tree improvement programs for three reasons. First, when most tree improvement programs were initiated (from the 1950s to the 1980s), aspen had very little economic value. It was considered an undesirable tree and its suckers an impediment to the growth of conifer seedlings which were favored. Second, in areas where aspen was desired, its coppicing ability made regeneration of the stand after harvest silviculturally simple and economically feasible. Therefore, there was no reason to develop an aspen program. Finally, hybrid aspen maintains all the attributes of native aspen with the added bonus of improved growth rates. For this reason, the majority of breeding work has been devoted to aspen hybrids and not native aspen.

There are two active aspen breeding programs in North America and both are based on a cooperative model. The Aspen/Larch Genetics Cooperative (ALGC) is currently located at the University of Minnesota but has its roots in the former Institute of Paper Science and Technology in Appleton, Wisconsin. The other cooperative aspen breeding program is the Western Boreal Aspen Corporation based in Edmonton, Alberta. Of the two, the ALGC is the only breeding program focusing solely on hybrid aspen and, in particular, crosses between quaking aspen and the European aspen (*P. tremula* L.). The *P. tremuloides* x *P. tremula* cross is particularly productive with a majority of families producing seedlings with hybrid vigor. Whereas native aspen grow from coppice at roughly 0.25-0.50 cords/ac/year, hybrid aspen families from this breeding program are growing at 1.0-2.5 cords/ac/year, approximately 4 to 10 times the growth rate of the native material (see Chapter 3 or Domke et al. (In review)). At these growth rates, hybrid aspen competes favorably with hybrid poplar and has the added advantage of deployment in an operational forest setting.

These growth and yield observations for hybrid aspen are based on the deployment of seedling-based families. Growth rates could be increased if clonal deployment were possible as in hybrid poplar. In clonal deployment the very best genotypes are selected, propagated and then planted in the field. This captures the entire genetic value of the superior genotype with virtually no tree-to-tree variation in the field. Hybrid aspen propagate readily from roots but not from hardwood cuttings like hybrid poplar. Additional gains in growth rate and yield could be attained if there were an economically feasible and reliable vegetative propagation method for hybrid aspen.

Accurate forecasting of hybrid aspen growth and yield would also benefit from volume functions for individual hybrid aspen trees. Currently, the only available volume functions are from a single Swedish study that looked at hybrids of *P. tremula* x *P. tremuloides* in Sweden (Johnsson 1953). Likewise, biomass equations for both native aspen and hybrid aspen in the Lake States would be beneficial for estimating total biomass on a site. Equations such as these are becoming increasingly necessary for accurately estimating both the total accumulated biomass and its economic value.

With the current emphasis on forest certification, there is increasing pressure to exclude the use of non-native or hybrid seedlings in artificial regeneration practices. In the case of hybrid aspen, the most discussed fear is introgression, or gene flow from the hybrid that dilutes the native gene pool. In reality, the issue is much more complex and a thorough investigation of the likelihood of introgression and its impacts is warranted. In order for any introgression of *P. tremula* genes into the *P. tremuloides* gene pool, several independent events must occur. First, the aspen hybrids must produce viable pollen. The pollen must then be transported to an individual *P. tremuloides*, where it produces seed. And finally, the resulting seed must land on a site where it can germinate and grow into an adult.

The first two events are not difficult to accomplish in the wild. Hybrid aspen are capable of producing viable pollen or receptive ovules, and crosses between hybrid aspen and *P. tremuloides* have been accomplished with ease in a controlled greenhouse setting (Institute of Paper Chemistry, 1988). The next step in the process of introgression is much more difficult. Once a backcrossed seed is produced, it must find an appropriate place to germinate and grow to sexual maturity. Establishing aspen literally from seed is extremely difficult and less frequent in today's environment than during the presettlement periods.

As a riparian species, aspen, like other *Populus* species, was found primarily along rivers and lakes that ebbed and flowed with seasonal adjustments in water levels. This riparian environment -- with its constantly shifting sandbars and scoured banks -- provided the moist, bare mineral soil with no competing vegetation that is required for establishing aspen from seed. After the harvest of the great pineries and the resulting slash fires from the 1880s to the 1930s, areas distant from rivers became more hospitable for establishing aspen from seed. In this way, the extensive aspen component in the Lake States region that currently exists became established. Today, with the exclusion of stand replacement fires and the control of seasonal river levels, the opportunities for establishing aspen from seed are extremely low. Thus, the opportunity for introgression between hybrid aspen and *P. tremuloides* is also extremely low.

In this discussion of the risk of planting hybrid aspen, it is imperative to include several additional facts related to hybrid aspen's genetic background and its life history traits. Hybrid aspen per se is not a genetically modified organism and by definition its genetic component is one-half native aspen. Therefore, there is no risk of an engineered gene escaping into the environment and each successive generation beyond the hybrid would have its *P. tremula* composition decreased by half, i.e., the first introgression event is really a backcross between a hybrid to a native aspen and results in a seedling with 25 percent of its genetic background derived from *P. tremula*. This first generation backcross introgressant would be composed of 75 percent *P. tremuloides* and 25 percent *P. tremula* genes.

P. tremuloides and *P. tremula* both belong to subsection Trepidae, section Leuce in the genus *Populus*. They are extremely similar morphologically and ecologically and, like all the members of Trepidae, they can be easily crossed (Einspahr and Winton 1977) and natural hybrids do occur where their ranges overlap (Barnes 1961; Andrejak and Barnes 1969) or where one species has been planted in proximity to another (Peto 1938;

Little et al. 1957). This information leads some investigators to consider these not as individual species but rather as a single circumpolar species with different varieties or races (Peterson and Peterson 1992).

One relatively unexplored method for controlling pollen and ovule production in hybrid aspen is to create triploid or 3N hybrid aspen for artificial regeneration. As triploids, these individuals have three copies of each chromosome instead of the regular two. Although native aspen with three copies of each chromosome are known in the wild (van Buijtenen et al. 1957; Every and Wiens 1971), during meiosis the chromosome pairings are so mismatched that virtually no viable pollen or ovules are produced (Johnson 1940). This natural sterility could be used alone or in conjunction with engineered methods of sterility to control the opportunities for introgression in hybrid aspen or genetically modified aspen.

2.3.3 Soils and site productivity

In the Lake States, aspen grows on a variety of soils (primarily Spodosols, Alifsols, and Inceptisols) ranging from shallow and rocky to deep loamy sand and heavy clays (Perala 1990). It grows best on well drained, loamy soils with high organic matter and nutrient content and where the water table is between 3 and 8 ft deep (Graham et al. 1963, Perala 1977, Perala 1990). Some of the most productive aspen stands across its range are in the northern part of the Lake States region and adjacent Canada where soils are cold, well-drained and rich in lime (Perala 1990). Despite this, most aspen in each of the three Lake States is found on moderately productive sites (Table 2.4).

There are many studies examining the effects of forest management activities on short- and long-term site productivity and nutrient availability (Bormann et al. 1968, Stone et al. 1979, Alban and Perala 1990, Pennock and van Kessel 1995, Morris 1997, Arikian et al. 1998, Grigal 2000, Stone 2001, Powers et al. 2005). The results of these studies vary widely with location, harvest methods, harvesting intensity and frequency, soil type, disturbance history, forest type, and climate (Bormann et al. 1968, Greacen E.L. and Sands 1980, Freolich 1977, Stone et al. 1979, Grier et al. 1989, Pennock and van Kessel 1995, Morris 1997, Arikian et al. 1998). The most notable effects of harvesting on forest soils and site productivity occur through the alteration of soil physical properties (Greacen and Sands 1980, Grier et al. 1989, Arikian et al. 1998, Grigal 2000). Changes in physical properties can persist for long periods, are not easily repaired, and can produce conditions outside the natural range of variability with negative effects on tree growth and site productivity (Froehlich 1977, Arikian et al. 1998, Grigal 2000). In contrast, nutrient depletion due to forest harvesting has not been well documented and requires long-term studies to see measurable effects (Grigal 2000). That said, it is generally accepted that whenever organic matter is removed from a site, there is also net loss of nutrients from that site (Grier et al. 1989). Those losses tend to be proportional to the volume removed, although total site nutrients stored in woody biomass differs for different forest types and sites (Grier et al. 1989).

In aspen-dominated ecosystems, there is a risk of nutrient loss and reduction in site productivity due to its rapid growth, reproduction strategies, and the fact that it accumulates more nutrients than its common associates (Alban 1982). In a study measuring soil compaction in 18 pure aspen and aspen hardwood stands in northern Minnesota, Arikian et al. (1998) found that soil compaction following harvests reduced regeneration density. They also found that decreased soil aeration and increased root damage inhibited root growth and productivity, limiting the resources available for residual tree growth (Arikian et al. 1998). In a similar study in northern Minnesota, Bates et al. (1993) found no significant evidence of soil compaction following clearcut but did document reduced aspen suckering in areas with increased rutting and soil scarification. Stone (2001) found that soil compaction negatively affected aspen sucker growth on clay sites across the Lake States but slightly increased sucker diameter and height growth on sandy sites. Alban and Perala (1990) kept compaction and soil displacement to a minimum to examine the impacts of biomass removal (whole-tree clearcutting and merchantable bole clearcutting) on soil nutrients and site productivity in aspen stands in the Lake States. When compared to control plots, they found that whole-tree and merchantable-bole harvesting had few short-term effects on soil organic matter and nutrient dynamics. In northern Quebec, Bellaeu and others (2006) found that whole-tree and stem-only harvesting decreased forest floor net C mineralization to net N mineralization (Cmin/Nmin) ratios and soil potassium (K) and increased extractable phosphorous (P), Kjeldahl N, base cation concentrations of calcium and magnesium (Ca and Mg), base saturation, pH, and effective cation exchange capacity increased. Two years after harvesting, no significant changes in soil minerals were observed.

While it is clear that forest management activities have a variety of impacts on forest soils and site productivity, the long-term effects of these activities are still largely unknown for aspen types. There is a need for more short- and long-term assessments of the effects of different harvesting strategies and equipment on aspen site productivity. These studies must be carried out across the dominant soil types which support aspen in the Lake States to track changes in soil physical properties, nutrient mineralization rates, and organic matter decomposition. These studies will become increasingly important as stand management for energy (which often calls for short rotations and significant biomass removals) becomes more common in the Lake States.

2.3.4 Forest health

A variety of biotic and abiotic agencies affect the health and vigor of aspen dominated ecosystems in the Lake States. Increases in atmospheric CO_2 and tropospheric O_3 can alter ecosystem structure and function (Kubiske et al. 2007). In northern Wisconsin, a free air carbon emission study by Kubiske et al. (2007) showed that elevated CO_2 encourages aspen growth and gives it a competitive advantage over two common associates, white birch (*Betula papyrifera* Marsh.) and sugar maple (*Acer saccharum* Marsh.) when compared to control stands. However, under elevated O_3, aspen growth was reduced and mortality increased when compared to the two associates and the control plots (Kubiske et al. 2007). In pure aspen stands, there were large clonal differences in growth rate and mortality under elevated CO_2 and O_3 conditions, suggesting that rates of ecological succession may be altered in the future (Kubiske et al. 2007).

Other abiotic factors such as wind, drought, flooding, fire, hail, and extreme temperature fluctuations also impact aspen ecosystem health. These agents can, in some cases, lead to direct mortality but more often cause tree damage creating opportunities for secondary pests and pathogens (Manion 1991). Weather events such as derechos, tornadoes, and floods following major weather events damaged 69,171 acres of aspen timberland in the Lake States during the most recent FIA inventory period (Figure 2.6). Fire was a relatively minor problem over the 2004-2008 inventory period, only damaging 18,085 acres across the region (Figure 2.6).

The aspens have two primary defense systems to guard against damaging biotic agents. The first is chemical defense where aspen accumulates phenolic glycosides and condensed tannins in tissues and coniferyl benzoate in flower buds (Lindroth 2001). The phenolic glycosides are toxic to a variety of pathogens, insects and small mammals, while coniferyl benzoate is toxic to ruffed grouse (Lindroth 2001). The second defense strategy is aspens capacity to maintain growth and reproduction after repeated defoliation events (Lindroth 2001). This strategy is particularly advantageous for the aspens which are hosts to several outbreak folivores which have the potential to cause extensive and uniform damage during peak periods of defoliation (Lindroth 2001).

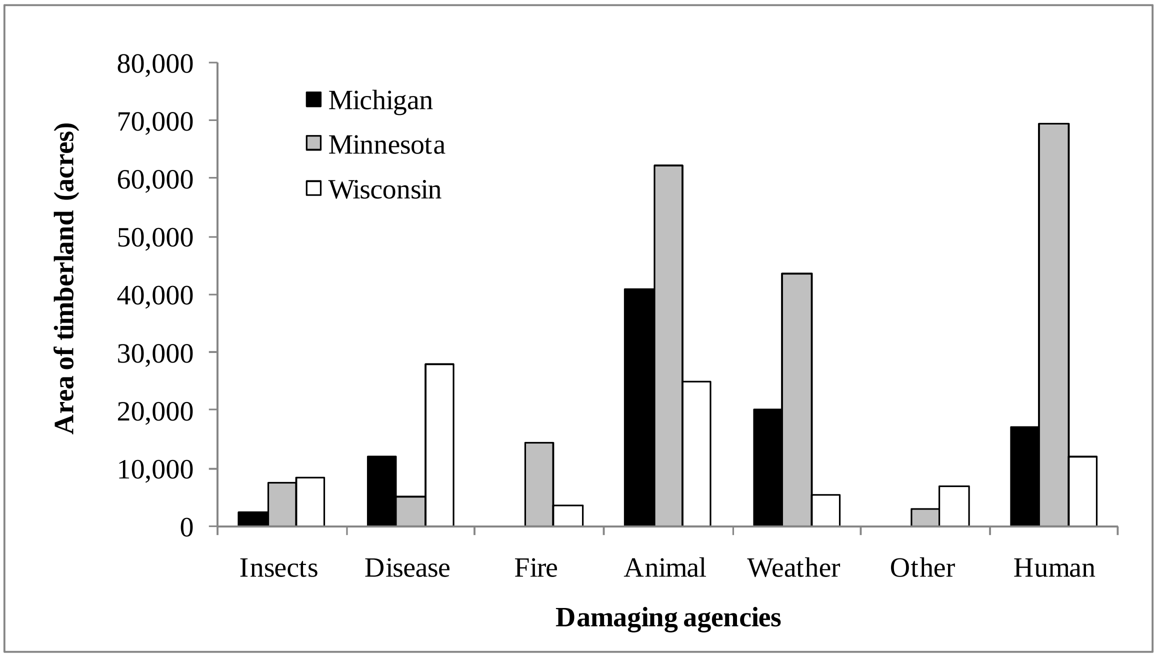

Figure 2.6 Area of aspen timberland damaged by biotic and abiotic agencies during the 2004-2008 inventory period in the Lake States.

Animals, domestic and wild, damaged 128,130 acres of aspen timberland during the latest inventory period in the Lakes States (Figure 2.7). Domestic (livestock) animals can cause tree damage through grazing and trampling and can reduce soil quality through compaction (Krzic et al. 2004). White-tailed deer (*Odocoileus virginianus* Goldman and Kellogg) and other wild ungulates can also cause damage through compaction but more often from browsing. Beavers (*Castor canadensis* Kuhl) can damage aspen directly by cutting and feeding on sapling to mature sized trees, and indirectly, by dam building which leads to flooding (Skinner 1984, Debyle and Winokur 1985). Small mammals such as rabbits, hares, mice, and voles feed on aspen bark, especially during winter months, which can result in mortality, particularly on small sprouts (Debyle and Winokur 1985).

Insects also play a major role in the aspen ecosystem health. There are many insect which prey on the three tree species, but only a few cause widespread damage. Insects damaged 18,367 acres of timberland during the most recent FIA inventory period in the Lake States (Figure 2.7). The forest tent caterpillar (*Malacosoma disstria* Hübner) is a major contributor to this damage, defoliating thousands of acres of aspen in some years. Outbreaks occur every 6 to 16 years, each lasting 4 to 5 years (Peterson and Peterson 1992). During the outbreaks, insects can defoliate entire trees (sometimes over multiple years), resulting in reduced vigor and, in some cases, death (Peterson and Peterson 1992). With the exception of the forest tent caterpillar, no insect defoliates more aspen than the large aspen tortrix (*Choristoneura conflictana* Walker). Outbreaks typically precede forest tent caterpillar outbreaks and last 2 to 3 years before the population crashes (Ostry et al. 1989, Peterson and Peterson 1992). During outbreaks, the tortrix consumes buds and leaves causing growth declines and, in extreme cases, death. The last insect pest, the gypsy moth (*Lymantria dispar* L.), is native to Europe and Asia and was introduced near Boston, MA in the 1860s. It has since spread west to the Lake States where individual insects have been found. The gypsy moth caterpillar feeds on the foliage of hundreds of different plant species but its most common hosts are oaks and the aspens. With the large aspen resource in the Lakes States, it is likely that the gypsy moth will become a more frequent defoliator as it continues to expand throughout the region.

Hundreds of diseases affect the aspens across the Lake States, however only a few cause large scale damage and mortality (Lindsey and Gilbertson 1978, Ostry et al. 1989). Most of the fungi associated with the aspens affect standing dead or fallen trees and are of minor importance to live aspen (Lindsey and Gilbertson 1978, Peterson and Peterson 1992). During the most recent FIA inventory period, diseases damaged 45,227 acres of aspen timberland (Figure 2.7). The fungus *Phellinus tremulae* (Bond.) Bond. & Borisov causes white trunk rot in living aspen and results in more volume loss than any other disease (Lindsey and Gilbertson 1978, Ostry et al. 1989). The spores from the fungus land and germinate in wounds on aspen stems and dark brown, hoof-shaped conks develop and lead to decay (Ostry et al. 1989). The fungi is most common in over-mature aspen stands where branch breakage and stem damage are common and in young stands which were damaged during mechanical thinning. Another fungus which affects aspen in the Lake States is the Hypoxylon canker (*Entoleuca mammatum* (Wahlenberg) J.D. Rogers and Y.-M. Ju (syn. *Hypoxylon mamatum* (Walhenberg) P. Karst). This fungus is the most common and damaging disease of quaking aspen and, like *Phellinus*, infects trees through wounds on stems and branches (Lindsey and Gilbertson 1978, Ostry et al. 1989, Ostry and Anderson 2009). Once the spores have germinated, the fungus grows rapidly into the main stem where it girdles and kills the tree (Ostry and Anderson 2009). It is most common in understocked stands and where bark feeding mammals or insects wound stems and branches and in stands damaged during thinning operations (Ostry et al. 2004). Armillaria root disease and butt rot are caused by several species of fungi in the *Armillaria* genus. It is most common in stressed or over-mature trees but is also found in highly productive aspen stands managed on short rotations (Stanosz and Patton 1987a, Ostry et al. 1989, Peterson and Peterson 1992). It spreads from tree to tree by rhizomorphs which grow through the soil until they contact and infect the root system of uninfected trees (Peterson and Peterson 1992). Armillaria root rot may limit rotation length and the number of times that aspen stands can successfully regenerate vegetatively (Stanosz and Patton 1987b, Peterson and Peterson 1992).

There has been a limited amount of research on management strategies to mitigate the effects of insect pests and pathogens on aspen in the Lake States. Some work on chemical, mechanical, and biological control agents has been conducted, but the results are often site- or clone-specific. More work is needed, particularly as it relates to early thinning, clonal selection and disease resistance. Studies examining the effects of global climate change on insect outbreak patterns and the associated interactions with aspen are also appropriate. There is also a shortage of studies documenting the mechanisms driving various biotic and abiotic interactions which affect aspen forest health. Further study on the biology and ecology of Armillaria root disease in managed stands is also needed, particularly on productive sites. Finally, as the gypsy moth continues to expand its range, monitoring should continue and control measures should be taken wherever possible.

2.3.5 Wildlife habitat

Aspen-dominated ecosystems provide food, cover, and breeding habitat for a variety of wildlife species (Gullion 1977, Gullion 1984, Debyle and Winokur 1985, Hoover and Wills 1987). In the Lake States, the two species most commonly associated with aspen forests are the white-tailed deer and ruffed grouse (*Bonasa umbellus* L.) (Graham et al. 1963, Byelich et al. 1972, Gullion 1977, 1984, 1987, 1990). White-tailed deer rely on young aspen stands primarily for food (Byelich et al. 1972). The prolific root suckering ability of aspen provides abundant, highly-palatable foliage during the spring and summer months (Byelich et al. 1972). As aspen stands begin to self-thin into evenly-spaced poles, they provide ideal vertical cover for ruffed grouse (Gullion 1990, Peterson and Peterson 1992). Ruffed grouse prefer to feed on male aspen clones which are 30-50 years old (Peterson and Peterson 1992). They feed on the foliage during the summer, staminate flower-buds during the winter, and catkins in early spring (Gullion 1990). The highest concentrations of ruffed grouse are found in areas where there are a variety of aspen age classes available for food, drumming structures, and cover (Gullion 1990).

Other wildlife species also use aspen-dominated ecosystems. Black bear (*Ursus americanus* Pallas), feed on aspen catkins and leaves in late spring after emerging from their dens (DeByle and Winokur 1985, Rogers et al. 1988). Beaver feed on stems and branches and use aspen as construction material for dams and lodges (Skinner 1984). Cottontail rabbits (*Sylvilagus nuttalli* Bachman), snowshoe hare (*Lepus americanus* Erxleben), and porcupines (*Erethizon dorsatum* L.) feed on the bark of young aspen stems (Graham et al. 1963, Banfield 1974). Many small mammals -- including shrews, mice, chipmunks, and voles -- inhabit aspen understory environments (D.A. West worth and Associates Ltd. 1984, Moses and Boutin 2001). These species play an integral part in the trophic dynamics of forests as both prey for large carnivores and as consumers of insects and other invertebrates, plant material (particularly fruits and seed), and fungi (Hamilton Jr. 1941, Westworth et al. 1984, Peterson and Peterson 1992, Carey and Johnson 1995, Elkinton et al. 1996, Moses and Boutin 2001).

Aspen stands also provide habitat for a variety of bird species (Thomas 1979, DeByle and Winokur 1985, Yahner 1991, Peterson and Peterson 1992, Schulte and Niemi 1998). Many of these species specifically rely on standing (snags) and downed material for drumming, excavation, nesting, and shelter (Thomas 1979, Petit 1985, Gullion 1990, Telfer 1993, Schulte and Niemi 1998). Schulte and Niemi (1998) documented 53 bird species in burned and logged aspen stands in northern Minnesota. The most common species were the Nashville warbler (*Vermivora ruficapilla*), chestnut-sided warbler (*Dendroica pensylvanica*), mourning warbler (*Oporornis agilis*), common yellowthroat (*Geothlypis trichas*), white-throated sparrow (*Zonotrichia albicollis*), and song sparrow (*Melospiza georgiana*) (Schulte and Niemi 1998). In a study comparing bird diversity in recent clearcuts and clearcut with residual (uncut) patches, Merrill et al. (1998) documented many of the same species as Schulte and Niemi (1998) in residual patches. In the clearcuts without residual patches, the most common species were the veery (*Catharus fuscescens*), least flycatcher (*Empidonax minimus*), ovenbird (*Seirus aurocapillus*), winter wren (*Troglodytes troglodytes*), rose-breasted grosbeak (*Pheucticus ludovicianus*), Canada warbler (*Wilsonia canadensis*), and black-throated green warbler (*Denroica virens*) (Merrill et al. 1998).

Most of the research examining wildlife habitat values of aspen-dominated ecosystems in the Lake States has focused on game species, particularly white-tailed deer and ruffed grouse. There is a shortage of information on aspen ecosystems as non-game habitat. Assessments of game and non-game species abundance, inter- and intraspecific interactions, and habitat usage are needed in order to develop new wildlife management recommendations and amend current practices. Strategies to incorporate wildlife management into current silvicultural practices for aspen and mixedwood stands are also of interest.

2.4 Silviculture

Aspen stands in the Lake States have historically been managed with the clearcut-coppice silvicultural system, where the nominal rotation age is often determined by the culmination of mean annual increment or a diminishing economic rate of return (Perala 1977, Puettman and Ek 1999). In practice, however, rotation age has much to do with achieving merchantable tree size for economic harvesting. A typical silvicultural prescription called for mature aspen stands to be clearcut at age 40 to 60 years (depending on site and clone) thereby creating near optimal conditions for root suckers to become established. The ramets self-thin as the stand matures and, at maturity, the process is repeated (Cleland et al. 2003). This rather simplistic approach has been used for decades in situations where net volume yield, wood uniformity, and sustainability (regeneration in this case) have been the primary management objectives. With the cost of regeneration being very low (typically just the harvest cost), this approach has also proved economically attractive.

In recent years, forest management practices in the region have begun to focus less on timber production and more on practices which meet environmental standards (e.g., for forest certification) and maintain the structure and function of ecosystems for various objectives. Table 2.5 summarizes historic and contemporary aspen management objectives and corresponding silvicultural treatments documented in the Lake States. Some treatments listed have been conducted on an experimental basis while others are commonly used in practice. In order to address changing forest management interests, forest managers must mix traditional silvicultural techniques (e.g., clearcutting) with contemporary approaches (e.g., early and commercial thinning, variable density thinning, retention patches in clearcuts, and clearcutting with residuals) to manage for non-timber objectives or multiple objectives, while capitalizing on specific aspen characteristics, e.g., its regeneration ability, clonal nature, and high level of genetic diversity (Perala 1977, Weingartner and Doucet 1990, David et al. 2001). Such management complexity is especially evident on public lands. However, short- and long-term changes in yield with the adoption of complex management practices have not been carefully examined. For example, in leaving competing tree species, yields may be reduced and aspen acreage lost. Additionally, the environmental gains from such management practices have not been well documented. For example, the various practices may favor biological diversity and/or certain wildlife species over others, yet terms such as diversity are difficult to define. Further, the stated desired conditions can be short lived and expensive to maintain. Old growth or aesthetics can be especially fleeting objectives with expensive consequences for subsequent restoration or conversion. Finally, most of the contemporary non-timber management objectives have been developed at the stand level, based on ecological, habitat, or aesthetic concepts and interests, with little quantitative attention to the overall forest implications for yield, costs, operational or long term management considerations. This situation indicates the scheduling of the various non-timber focused treatments and stand conditions across large ownerships is a neglected activity in practice and a potentially very instructive area for research.

A renewed interest in early or precommercial thinning has occurred in recent years because of the predicted aspen timber shortages in the Lake States due to an imbalance in the aspen age class structure. This imbalance is a result of the rapid 1850 to 1930 harvest of the original mature pine and other mixed forest and its replacement by aspen as the dominant forest type. The result has been characterized as a “wall of wood” moving forward across the region as the aspen has matured. Harvesting overall has tended to replace older stands by younger ones; in part as an attempt to create an equal distribution of acres in each age class. However, as harvesting has varied by decade and location, the age class structure remains uneven and younger stands have not yet reached merchantable size, thus the apparent shortage of aspen until they do so. Importantly, even then, reduced acreages of aspen may still limit supplies. As a result of the aspen supply problem, there has been an increased emphasis on obtaining high quality fiber from younger stands (David et al. 2001). In young aspen stands where sucker and sprout densities are very high (up to 20,000 to 30,000 stems/ac), precommercial thinning has been used to shorten the length of pulpwood rotations, promote the diameter growth of residual stems, and favor superior clones (Graham et al. 1963, Perala 1977, Jones et al. 1990). Another technique used to favor superior clones and thus shorten rotation lengths in heavily stocked juvenile stands is “stem flattening.”

Table 2.5 Silvicultural practices for aspen management in the Lake States (adapted from Cleland *et al.* 2003).[a]

Silviculture	Management Objective				
	Timber/Fiber Production			Wildlife habitat or diversity	Old growth or aesthetics
	Natural	Managed	Plantation		
Harvest	Clearcut commercially mature stands	Clearcut commercially mature stands	Clearcut commercially mature stands	Clearcut or variable retention of other desirable species	None[b], variable aspen retention, clearcut, or burn as stand breaks up
Size of harvest units	Generally large (25+ acres) or entire stand	Generally large (25+ acres) or entire stand	Generally large (25+ acres or entire stand	Extremely variable depending on habitat objectives	<5 acres to entire stand
Rotation or cutting cycle	35 to 70 years[c], depending on site and clones	30 to 70 years[c], depending on site and clones	15 to 30 years[c], depending on site and clones	20 to 80+ years depending on the area age class distribution	60-120+ years
Site preparation	None[d], except where a dense understory of tolerant trees requires cutting, disking, burning or herbicide treatment	None[d]	Variable; extensive chemical and mechanical in agroforestry setting, some chemical and/or mechanical in operational forestry setting	None[d]	None[d]
Tending	None	Precommercial thinning for dense stands or commercial thinning to expand desirable clones or capture early economic return	Agroforestry - 2 to 3 years mechanical and chemical vegetation control; shearing option at 6 to 12 years for seedling derived plantations	Generally none	Optional; thinning will produce large-diameter trees more quickly
Overstory composition	Pure stands preferred (less than 15 percent other tree species)	Pure stands preferred (less than 15 percent other tree species)	Pure stands preferred	Pure or mixed species, multistoried stands depending on habitat objectives	Pure or mixed species, multistoried stands

[a] This table highlights silvicultural practices prescribed to accomplish different management objectives in the region. Many of the practices used to achieve a particular objective have proven useful in meeting other management objectives (e.g., clearcutting for timber production also benefits certain wildlife species). In all cases retention of aspen is the goal.

[b] No management or disturbance may lead to succession from aspen to other species.

[c] Very short rotations (less than 20 years) may lead to deterioration of aspen root systems.

[d] Provided adequate potential for sucker reproduction exists.

This technique typically results in alternating strips (6 to 8 ft wide) of flattened, but not severed, juvenile aspen stems (8 to 10 years old) and untreated strips (6 to 10 ft wide) (Zasada et al. 2000, David et al. 2001, Cleland et al. 2003).The flattened stems are killed and the new suckers are suppressed under the shade of the residual strips. In severely understocked juvenile aspen stands, shearing has been an effective technique used to restore full stocking (Perala 1983, Domke et al. (In review)). However, data on the effectiveness of these approaches in terms of yield is very limited.

The interest in thinning has also been stimulated by the introduction of new harvesting technologies, specifically cut-to-length (CTL) whole tree processors. These processors can greatly reduce damage to the residual stand because of their improved maneuverability relative to older harvesting equipment (David et al. 2001) and a reduction in skidding damage. Some CTL equipment operating on clearcut travel strips can reach as far as 23 ft into a stand that is being thinned. Feller buncher harvesting equipment may also be used in this manner. Commercial thinning has been recommended for aspen growing on good sites (site index 80 or better) that are at least 20 to 30 years old and have basal areas of 120 to 140 ft^2/ac (Perala 1977, David et al. 2001).

Depending on management objectives, thinning from above (which calls for the removal of co-dominant and dominant trees to release other co-dominant and intermediate individuals) or below (which calls for the removal of suppressed and intermediate trees to favor co-dominant and dominant individuals) could easily be implemented with CTL harvesting equipment. Furthermore, variable density thinning (a technique which calls for unthinned areas and heavily thinned patches, along with variable levels of thinning and residual density) could be carried out with CTL equipment. Again, the yield response in terms of mortality salvaged and increased growth of the residual stands from such practices is not well documented for the range of clones, sites, and locations germane to aspen management across the region.

Clearcutting with reserves or retention harvesting can be thought of as a continuum from uniformly distributed to highly aggregated (David et al. 2001). This silvicultural approach may be a viable option in even-aged aspen stands where the primary objective is to convert the stand to a multi-cohort, mixed species assemblage. Again, the yield response and non-timber (e.g., biodiversity) gains, if any, are not well documented.

Given an interest in both pulpwood and biomass for energy, improved native aspen or hybrid aspen managed in plantations may also become more common across the region. Currently, superior clone selection is practiced in native stands where the desire is to improve stem form or growth potential of the stand (Perala 1977). The possibility for long-term genetic improvement of an aspen stand exists, however there are some drawbacks. First, it is difficult to identify individual clones during winter (leaf off) harvest conditions so inferior clones are often left unintentionally. Second, elimination of unwanted clones, even with the use of herbicides, is not always effective. Assuming plus clone selection were to be practiced during consecutive harvests in the same stand, the potential for changing stand genetics is great but does require multiple selection events.

Several decades of research in the Aspen/Larch Genetics Cooperative at the University of Minnesota have demonstrated improved growth with three distinct plantation approaches; intensively managed, conventional, and dense packs. Although it is possible to use either native aspen or hybrid aspen in a plantation setting, hybrid aspen is typically deployed due to its superior growth rate.

The intensively managed plantation method is identical to hybrid poplar culture, with extensive alteration of the ground (competing) vegetation and soil surface through mechanical and/or chemical site preparation and vegetation management for the first two to three years until crown closure is attained. This method exploits the genetic potential of aspen seedlings by reducing competing vegetation and supplying seedlings with necessary resources during early stand development. For the production of pulpwood and biomass for energy, realistic rotation ages for both hybrid aspen and hybrid poplar range from 12 to 20 years depending on site, growing conditions, genotypes used and success in controlling competing vegetation. Under these conditions, hybrid aspen competes well with hybrid poplar while providing wood fiber with superior whiteness and the ability to regenerate the site after harvest at minimal cost (David 2003).

The conventional approach is based on a conifer plantation model where site conditions, location and costs prohibit intensive management. In this approach, chemical and/or mechanical site preparation is used to prepare the site for planting aspen or hybrid aspen seedlings at a density of 540 to 890 per acre. After planting, control of competing vegetation is minimal with the use of herbicide as a release option and is encouraged if growth rates stagnate due to competition. At age 6 to 10 the plantation should be evaluated for stocking, growth rate, annual mortality rate, and incidence of insects and disease. This evaluation will assess the risk of carrying the existing plantation to harvest or, alternatively, sheering the entire hybrid aspen stand and regenerating the plantation from coppice. Although shearing appears to delay the time to harvest by the age of the plantation at shearing, the established root systems from the planted hybrids allow for rapid growth of the new suckers. This rapid growth decreases the discrepancy between the predicted harvest dates of the sheared and unsheared stands. As an added advantage, shearing will increase stocking and improve the average stem form (Domke et al. (In review)).

The third plantation approach has been called the dense pack design. In this case, small groups of 25 to 81 seedlings are planted at 1 to 2 foot spacing. The distance between these dense packs varies from 30 to 60 feet so that there are approximately 16-49 dense packs per acre. There are a few major differences between dense pack plantation establishment and the conventional method. First, in the dense pack design, the seedlings are planted in groups as opposed to a systematic grid pattern of single seedlings spread evenly across the whole site. Second, because the planted seedlings are in groups with unforested areas between them, the dense packs must be sheered once the root systems have establish in order for new suckers to capture the unforested areas and achieve full site stocking.

Mandatory shearing with the dense pack design does increase the length of the first rotation. Because the seedlings are grown together in groups, they are typically smaller than seedlings planted in the conventional method at the same age so shearing is recommended at the slightly older age of 8 to 12 years. Additionally, with this method there is the risk that if a dense pack is growing poorly or fails altogether, stocking levels in the vicinity of that dense pack will be low or non-existent. Understocked sites may require a second or third shearing to achieve adequate stocking. The primary advantages to the dense pack design are lower site preparation and tending costs because initial site preparation is required only in the vicinity of each dense pack and, when grown in groups, release efforts are typically not required. Also, seedlings are less susceptible to browse, vegetative competition and extreme climate conditions because the tightly spaced seedlings mimic the spacing found in a stand regenerating from coppice. Since dense packs are composed of a group of seedlings, it is possible to lose individual stems but still maintain an aspen presence and therefore the ability to regenerate a specific area. This concept is similar to a coppice derived stand where suppressed stems are outcompeted and die leaving dominant stems to control the site.

2.5 Economics

The economics of aspen management at the stand level can be attractive due to the relative ease of establishing aspen stands, simplicity of management, and potentially short rotations. Technological adaptations by industry to use aspen as a raw material for a wide range of manufacturing processes and products have resulted in a high demand for aspen roundwood, particularly for engineered wood products like oriented strand board (OSB) and waferboard (Balatinecz and Kretschmann 2001). This was not the case as recently as 25 years ago, when lack of markets in Minnesota necessitated programs that actually paid loggers to “recycle” old aspen stands. Aspen has also come to be appreciated as key habitat for certain wildlife, particularly game species. In particular, early to middle-age aspen stands provide important habitat for a variety of wildlife species. Before markets were established for aspen, much of the forest management in this type was conducted solely for improving wildlife habitat.

Figure 2.7 describes historical stumpage prices for Lake States aspen. Published prices of aspen roundwood sold by public land management agencies in Minnesota from 1989 to 2005 indicate an average annual increase (nominal) of over 17 percent (MNDNR 2006). While not as dramatic, aspen stumpage prices in Michigan and Wisconsin also increased considerably over this same time period. In 2006, a downturn in the housing market combined with aging facilities and the growing cost of production led to sharp declines in stumpage prices across the region, particularly in Minnesota (Figure 2.7).

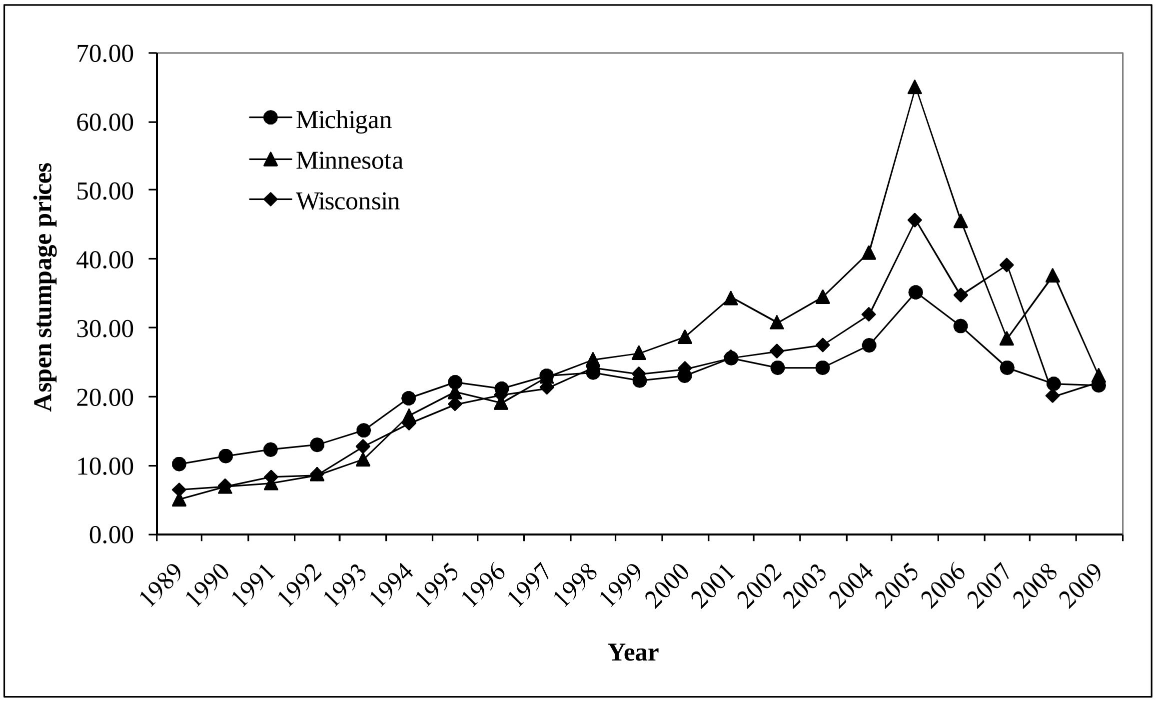

Figure 2.7 Historical stumpage prices for aspen pulpwood in the Lake States.

Kilgore and MacKay (2007) compared aspen stumpage and forest land value changes occurring from 1989 to 2003. Given the rapid increase (averaging 13 percent per year) in the median price of Minnesota forest land, the relationship between stumpage and forest land prices change was assessed during this period. Forest land capitalization rates, which are a measure of investment over time, were calculated from 1989 to 2003 using aspen stumpage prices and growth rates as a proxy for annual timber rents. During the first seven years of this time period, Minnesota's forest land capitalization rate increased to its peak of 3.2 percent, reflecting the substantial rise in stumpage prices relative to forest land values. After 1995, the capitalization rate steadily decreased to 1.2 percent in 2003 – just 0.1 percent below the capitalization rate that existed in 1990 and 0.3 percent above the 1989 rate. Thus, in spite of the rapid increase in forest land values and stumpage prices during this period, the competitiveness of forestry as an income-producing use of the land was greater in 2003 (when the median price of forest land was $981 per acre) than it was in 1989, when the median price of forestland was less than $200 per acre (Kilgore and MacKay 2007). Updated forest land sales and aspen stumpage price data through 2005 indicates the value growth of aspen relative to forest land has increased since 2003 but is still lower than when the trend reversed in 1995 (Kilgore and MacKay 2007).

Research on the economics of aspen management in the Lake States is almost non-existent and severely outdated. Ek and Brodie (1975) conducted one of the more thorough assessments of alternative strategies to maximize financial returns to the landowner according to the intensity of management, site quality, and product utilization. Other studies addressing the economics of aspen management include Husain (1996), Bella and Yang (1991), Hove (1990), Graham and Betters (1985), Nordeen (1968), Perala (1983), and Zasada (1952). Several of these studies are not specific to Lakes States aspen. Moreover, nearly all were conducted under vastly different market, price, cost, and utilization conditions than exist today.

It can be argued that aspen management has become a secondary consideration in aspen management at the stand level on some public forests. In contrast, many timber companies, counties and other forest owners are more sensitive than ever to the need for forest management investments to be successful in terms of stand outcomes, yields, and allowable harvest calculations. Harvest scheduling models (Hoganson and Rose 1984, Borges and Hoganson 1999, Wei and Hoganson 2005) have become an essential tool to providing forest management plans that are operationally feasible, financially efficient, and sensitive to the diverse environmental constraints faced in managing large forested landscapes. Such model-based planning can add great clarity about tradeoffs in choices involving rotation ages and stand treatments that affect outputs and services at the stand and forest level. The approach can also identify meaningful allowable harvests that less quantitative approaches have missed.

As an example of scheduling issues, consider that aspen in the 1 to 10 year age class is thought to be prime habitat for ruffed grouse. Managing aspen on 50 year rotations provides such habitat 20 percent of the time. However, managing some aspen stands on 40 year rotations provides such habitat 25 percent of the time. Clearly, rotation age choices and their distribution across the landscape are important considerations in wildlife management.

Finally, there is the increasing interest within state government to address the highly competitive and global nature of today's forest products industry. This interest is largely driven by the desire to retain jobs in the forest-based sector or encourage industrial expansion and the associated economic multiplier effect. While global forest products firms may view investments on a location and profitability basis, states may view investments in forest management as "jobs per 1,000 cords." Thus, stand-level economic considerations may pale in comparison to regional employment and ecosystem service needs. The Lake States forests, which have evolved into a complex set of public and private forest ownership conditions and associated policies and management strategies, have the potential to play a major role in fostering economic development. While this chapter necessarily considers the economics of stand-level aspen management, the possibilities and implications for larger scale investments need to be considered.

2.6 Research Needs and Strategies

This review has covered much of what we know about aspens and their management. Clearly, the retention of aspen and its management is important to the forest products industry and the diverse forest landowners in the Lake States for a variety of purposes. With this interest and the findings from review, it is apparent that research on aspen and its management has been very modest at best. This research needs further focus, organization and resources. The evident research needs include:

2.6.1 Resources status and trends

- Examine aspen covertype acreage losses with respect to contributing ecological, management and harvesting factors, including ownership. Additionally, the full set of economic and ecological implications and restoration strategies need to be developed.
- Develop improved growth and yield models for aspen management with capability for estimating the gains from the application of early and commercial thinning for pulpwood and energy potentials and including both stem and full tree utilization levels.

- Assess trends in aspen stand yields with respect to site conditions, location, disturbance history, and other stand characteristics.
- Develop volume functions for individual hybrid aspen trees to accurately forecast hybrid aspen growth and yield.
- Examine growth responses to early (precommercial) thinning treatments.
- Develop biomass functions for both native aspen and hybrid aspen in the Lake States for estimating total biomass on a site.

2.6.2 Biology and ecology

- Identify clone, site, insect and disease interactions to identify appropriate aspen management potentials and problems.
- Examine aspen insect and disease problems in early thinning operations.
- Examine aspen clonal resistance to decay fungi.
- Examine the biology and ecology of Armillaria root disease in managed aspen stands.
- Articulate tree and clone improvement strategies for traditional and intensive plantation management and for addressing the potential of climate change.
- Develop clonal propagation methods that are physiologically reliable and economically feasible.
- Develop clonal propagation methods that address the potential of climate change.
- Assess the mechanisms driving various biotic and abiotic interactions which affect aspen forest health.

- Assess harvesting impacts on site productivity, especially with respect to nutrient removal and future species composition.
- Thoroughly investigate the likelihood of gene flow from hybrid aspen to the native aspen gene pool and its impacts.
- Improve documentation of the ecological (e.g., biodiversity) contributions of managed aspen forests at the stand and landscape scales.
- Assess the game and non-game species abundance, inter- and intraspecific interactions, and habitat usage in aspen and mixedwood stands is necessary in order to develop new wildlife management recommendations and amend current practices.
- Develop strategies to incorporate wildlife management into current silvicultural practices for aspen and mixedwood stands.

2.6.3 Silviculture

- Assess management activities such as plus clone selection, clearcutting, and variable retention harvesting on genetic diversity at the stand level.
- Identify rotation ages and thinning strategies appropriate to timber and non-timber objectives that can serve multiple objectives.
- Articulate harvest scheduling strategies for entire forests that are conducive to timber, non-timber and multiple objectives over long time periods.

- Examine short- and long-term changes in yield with the adoption of complex management practices (e.g., early and commercial thinning, variable density thinning, retention patches in clearcuts, and clearcutting with residuals).
- Examine management strategies to mitigate the effects of insect pests and pathogens on aspen in the Lake States.
- Examine changes in yield from mortality salvaged and increased growth of the residual stands from thinning treatments for the range of clones, sites, and locations germane to aspen management across the Lake States.

2.6.4 Economics

- Conduct financial evaluations of aspen management regimes that incorporate alternative thinning, site-preparation, and final rotation strategies.
- Identify economic trade-offs associated with managing the aspen covertype on an extended rotation policy.
- Identify and evaluate important factors impacting capital investment decisions that utilize the aspen resource in the Lake States.
- Identify financial and economic implications of alternative land tenure arrangements and associated management strategies for the aspen resource.
- Identify strategies to increase the global competitiveness of the aspen resource as a wood fiber source in the Lake States.
- Estimate willingness to pay for aspen stumpage for roundwood and energy uses in the Lake States.

- Identify and evaluate economic trade-offs associated with managing aspen stands for fiber versus non-timber benefits (primarily older age stands for wildlife habitat) in the Lake States.

Research developed to address these needs will, in all likelihood, be conducted by existing university and agency research programs within the region. We recommend a substantial focus on aspen and these issues with targeted requests for proposals (RFPs) or other dedicated resources. Existing data from FIA and other sources should contribute to this effort. However, it will also be important to establish experiments and field trials on a level comparable to that already conducted for the most studied species in the region (red pine and white spruce). It may also be appropriate to establish an aspen cooperative of some type to develop and synthesize research on these topics. The Minnesota Tree Improvement Cooperative, where industry and agencies provide "in kind" support is one model for this effort. New information tools such as the web-based Forest Management Guides for the North Central Region (http://nrs.fs.fed.us/nfmg) (Domke et al. 2006) may be a particularly effective vehicle for transferring information and technologies to landowners.

Chapter 3

Hybrid aspen response to shearing in Minnesota: implications for biomass production

There is great potential for the production of woody biomass feedstocks from hybrid aspen stands; however, little is known about the response of these systems to silvicultural treatments, such as shearing. We sought to address this need by integrating results from more than 20 years of individual tree and yield measurements in hybrid aspen (*Populus tremuloides* Mich. x *P. tremula* L.) stands in north central Minnesota. Specifically, tree and stand-level responses are described in terms of sucker density, early diameter and height characteristics, volume, and biomass production. Overall, shearing treatments increased the density of hybrid aspen stems, relative to pre-shear densities at the same age. In addition, average stem diameter and volume as well as stand-level biomass were considerably greater in hybrid aspen stands relative to similarly aged native aspen stands also established via shearing treatment. These findings illustrate that coppice systems using hybrid aspen provide great potential to rapidly produce biomass feedstocks, with little management investment.

3.1 Introduction

Renewed interest in the use of woody biomass for energy has created an opportunity for the development of silvicultural systems that can produce high levels of biomass over shorter rotations than traditional approaches to plantation management (Weih 2004, Dickmann 2006). One area within this arena where there is a great deal of potential is the management of short-rotation hybrid aspen (Liesebach et al. 1999, Karacic et al. 2003, Rytter 2006). In particular, early successional hardwood tree species -- such as those in the *Populus* genus -- typically exhibit rapid initial height and diameter growth, making these species ideally suited for short-rotation forestry applications aimed at maximizing biomass production over short time scales (Johnsson 1953, Karacic et al. 2003, Rytter 2006). In many cases, greater levels of early growth have been achieved through the use of aspen hybrids, such as the cross between quaking aspen (*P. tremuloides* Michx.) and European aspen (*P. tremula* L.). The improved growth of hybrid aspen over the parental species is thought to be the result of heterosis. Li and Wu (1997) suggest that the improved growth of hybrid aspen might be due to overdominance interaction between two alleles, one from the *P. tremula* parent and the other from the *P. tremuloides* parent, at the same locus.

In addition to the rapid growth of these hybrids, their prolific root-sprouting presents potential management options for the production of woody biomass using coppice methods after initial plantation establishment (Liesebach et al. 1999). Moreover, the use of existing aspen root stocks as sources of regeneration for subsequent rotations provides a silviculturally straightforward and cost-effective means for sustaining these systems over multiple short rotations (Hoffman-Schielle et al. 1999). Finally, the expansion of aspen root systems with each subsequent rotation may provide a long-term opportunity for increasing belowground carbon storage on these sites (King et al. 1999). Most research on hybrid aspen has focused on the quantitative genetics and early growth of selected genotypes in highly controlled field and lab environments (Benson and Einspahr 1967, Li and Wu 1997, Tullus et al. 2007). Very few studies have examined the response of hybrid aspen to silvicultural treatments at operational scales. In the mid 1980s, the Aspen/Larch Genetics Cooperative at the University of Minnesota began a series of hybrid aspen planting trials in north central Minnesota. These trials were initiated to compare hybrid aspen (*P. tremuloides x tremula*) stand characteristics to native aspen (*P. tremuloides*) stand characteristics on similar sites. In the mid to late 1990s, the hybrid aspen stands were sheared to compare hybrid aspen sucker density and growth with native aspen suckering and growth. Shearing is an effective technique for stopping the flow of auxin from the aboveground portion of the tree to the root system, initiating the development of new meristems and preexisting primorida on the roots, which often develop into suckers (Schier 1981, Perala 1983, Frey et al. 2003). During that period, two native aspen stands, which were representative of much larger aspen sites in the study area, were added to the study to more closely compare hybrid aspen stand attributes with native aspen stand attributes. Funding and personnel changes, as well as operational constraints over the 23 year study period, limited sampling and measurement in certain years. Nevertheless, this study is one of the largest and longest of its kind and the data provide useful reference points for future studies on hybrid aspen growth and yield.

The study results are used to examine (1) regeneration response of hybrid aspen pre- and post-shearing, (2) native and hybrid aspen tree characteristics (height, diameter, and volume) pre- and post-shearing, and (3) native and hybrid aspen volume and biomass production post-shearing. In addition, the findings are used to evaluate potential silvicultural options for managing hybrid aspen stands and their implications to carbon storage and biomass production for energy.

3.2 Methods

3.2.1 Site conditions and treatment history

This study was conducted in five stands located near Grand Rapids, Minnesota (47° 15’N, 93° 30’W). The most common soil type on the sites was Stuntz very fine sandy loam (Glossoboric Hapludalf; Natural Resources Conservation Service 2009). All sites had the same ecological classification (UPM Blandin Paper Company system) with site indices ranging from 21.3-24.4 meters (m) for native aspen at a base age of 50 years (Cheryl Adams, UPM Blandin Paper Company, personal communication November 6, 2009). The climate is continental with warm summers (mean July temperature 20 °C), cold winters (mean January temperature -14 °C), and 731 mm of precipitation, about half of which occurs during the growing season (National Oceanic and Atmospheric Administration 2004). The five sites were treated with glyphosate (Accord) prior to planting and sheared at different dates over the course of the study (Table 3.1). All sites were sheared in late winter or early spring under frozen ground conditions to minimize damage to root systems. Shearing was consistent on all sites and occurred by cutting and felling stems with a “KG” blade mounted on a crawler tractor. The shearing equipment used in this study was to apply a treatment without cost consideration. Current methods often utilize brushsaws. Table 3.1 summarizes stand information. All hybrid aspen stands in the study were planted with a mixture of hybrid aspen families to ensure genetic diversity and ameliorate major pest problems (Roberds and Bishir 1997, Weih 2004).

Table 3.1 Description of study sites, sample sizes, and site activities.

Site	Area (ha)	Site index (m at base-age 50)	Date	Stand age (yrs)	Site activity	Number of plots	Plot size (m2)
Hybrid 1	12	24.4	Mar-86	1	Planted		
			Jan-98	13	Sampled	28	81
			Mar-98	13	Sheared		
			Dec-98	1	Sampled	26	4
			Aug-01	4	Sampled	23	10
			Apr-08	10	Sampled	27	16
Hybrid 2	8	21.3	May-86	1	Planted		
			Mar-93	8	Sampled	16	405
			Mar-94	8	Sheared		
			Nov-98	5	Sampled	14	4
			May-08	14	Sampled	23	16
Hybrid 3	12	21.3	Apr-91	1	Planted		
			Dec-97	7	Sampled	26	81
			Mar-98	7	Sheared	19	4
			Apr-08	10	Sampled	26	16
Native 1	2	21.6	Jan-98	1	Clearcut		
			Apr-08	10	Sampled	5	16
Native 2	2	21.6	Jan-98	1	Clearcut		
			Apr-08	10	Sampled	5	16

3.2.2 Sampling methods

Plot and sample sizes varied across sites and sample periods in this study (Table 3.1). Permanent plot centers were established in the Hybrid 1 and Hybrid 3 sites and non-permanent plots were taken in the Hybrid 2, Native 1, and Native 2 sites. In all cases, a systematic line plot design was used with transect locations determined by a random start and plot centers established along these transects. All live native and hybrid aspen stems were measured in each plot. This is noteworthy since hybrid aspen suckers may develop from the established root systems of the planted hybrid aspen seedlings prior to shearing.

The tree variables of interest in this study were stems per hectare, diameter at breast height (dbh), total tree height, individual tree volume, total stand volume, and above-ground biomass production. Tree diameter was measured at 1.3 meters (m) above-ground using calipers, and total height was measured using a telescoping measuring rod or, when necessary, a digital hypsometer. Stem volume was calculated using individual tree height and diameter information and an equation originally developed by Gevorkiantz and Olsen (1955) and modified by Ek (1985) for small aspen stems:

$$V = FBH$$

where, V = the peeled volume of an individual stem (m^3), F = the cylinder form factor, [for trees < 9.14 m in height, $F = 0.42 + 0.02(9.14-H)$; for trees $\geq$ than 9.14 m, $F = .42$], B = the basal area (m^2) computed from dbh outside bark, and H = tree height (m). Stand volume estimates were calculated according to Ek and Brodie (1975):

$$Vs = 0.4972(H - 4.5)^{1.9139} N^{0.1439}$$

where, Vs = total stem volume (1 ft^3/ ac = 0.0670 m^3/ha) from 0.15 m stump to tip of all trees ≥ 0.30 m tall, H = average dominant height (ft, 1 ft = 0.3048 m), and N = trees per acre (1 acre = 0.405 ha). Individual tree biomass was calculated according to Jenkins et al. (2003):

$$bm = Exp(\beta_0 + \beta_1(\ln)dbh)$$

where, bm = total aboveground oven-dry biomass (kg) for trees 2.5 cm dbh and larger, β_0 = -2.2094, β_1 = 2.3867, dbh = diameter at breast height (cm), Exp = exponential function, and ln = natural log base “e” (2.718282).

3.2.3 Data analysis

Due to the variability in plot and sample sizes across sites and sample periods, and the lack of control plots at each site, only descriptive statistics were used to analyze treatment effects, tree characteristics, and yield information. Plot-level data was used throughout the analysis. All statistical analysis was conducted using R statistical software, version 2.10.0 (R: A Language and Environment for Statistical Computing, version 2.10.0, 2009).

3.3 Results

3.3.1 Stem density

Pre- and post-shear stem density information is presented in Table 3.2. There was considerable variation in stem density across plots within hybrid aspen stands, but mean stem density increased on all three sites following shearing. Ten years post-shearing stem density in the Hybrid 1 site was nearly 3.9 times (mean = 6,521) that of the 13 year old pre-sheared stand. The Hybrid 3 site had 1,483 stems/ha seven years post planting and ten years after shearing stem density increased nearly 3.0 times to 4,396 stems/ha. The Hybrid 2 site had substantially fewer stems (mean = 570) than the other two hybrid aspen sites prior to shearing. Fourteen years post-shearing, stem density increased nearly 3.8 times that of the pre-sheared stand to 2,149 stems/ha. Due to the late addition of the native aspen stands, stem density was not measured prior to shearing. Ten years post-shearing the Native 1 and Native 2 sites had 7,537 stems/ha and 8,525 stems/ha, respectively.

Table 3.2 Pre-and post-shear stem density information for the five study sites.

				Stems per hectare		
Site	**Age**	**Status**	**Type**	**Mean**	**Standard Deviation**	**Coefficient of Variation (%)**
Hybrid 1	13	Pre-shear	Sapling	234	261	112
			Sucker	1,456	1,150	79
			Total	1,690	1,274	75
	1	Post-shear	Sucker	32,790	23,355	71
	4	Post-shear	Sucker	40,720	27,171	67
	10	Post-shear	Sucker	6,521	4,410	68
Hybrid 2	8	Pre-shear	Sapling	406	340	84
			Sucker	164	185	113
			Total	570	445	78
	5	Post-shear	Sucker	8,119	6,387	79
	14	Post-shear	Sucker	2,149	1,776	83
Hybrid 3	7	Pre-shear	Sapling	504	275	55
			Sucker	979	867	89
			Total	1,483	966	65
	1	Post-shear	Sucker	14,177	11,409	80
	10	Post-shear	Sucker	4,396	3,326	76
Native 1	10	Post-shear	Sucker	7,537	1,874	25
Native 2	10	Post-shear	Sucker	8,525	4,377	51

3.3.2 Tree characteristics

Given that the sampling periods were not aligned for the different sites and the shearing treatments occurred at different times, data were combined according to pre-and post-shear stand ages to focus our analysis of tree characteristics and yield information. Pre- and post-shear site combinations and tree characteristics are summarized in Table 3.3.

Pre-shear hybrid aspen suckers (which arose from the planted seedlings and were several years younger at the time of shearing) and saplings were compared on the Hybrid 2 and Hybrid 3 sites (Table 3.3). The pre-shear hybrid aspen saplings were more than 1.5

times (mean = 4.54) taller than pre-shear hybrid aspen suckers (mean = 2.89) and there was less variability within the sample (CV = 32%). Pre-shear saplings also had greater diameter growth (mean = 3.38 cm) than the hybrid aspen suckers (mean = 1.60 cm) on the two sites and substantially higher individual tree volume and biomass production than hybrid aspen suckers (Table 3.3). Pre-shear hybrid aspen tree characteristics on the Hybrid 2 and Hybrid 3 sites were also compared to post-shear native and hybrid aspen sucker characteristics. In all cases, post-shear native and hybrid aspen tree characteristics were greater than pre-shear values (Table 3.3).

Post-shear aspen suckers from the Hybrid 1 and Hybrid 3 sites (both age ten) were compared to aspen sucker characteristics on the Native 1 and Native 2 sites of the same age. Hybrid aspen suckers were more than 1.5 times taller (mean = 2.18) than native aspen suckers (mean = 1.41) with no difference in height variability between the grouped sites (CV = 24%). Aspen sucker diameters in the Hybrid 1 and Hybrid 3 sites were nearly 1.7 times greater than sucker diameters in the Native 1 and Native 2 sites with a small difference in diameter variation between the two grouped sites (Table 3.3).

Table 3.3. Descriptive statistics of the measured and calculated individual tree characteristics: tree height (m), diameter at breast height (dbh) (cm), and volume (dm^3) for grouped sites: Hybrid 3 (age seven) and Hybrid 2 (age eight) aspen saplings and suckers prior to shearing treatments, Hybrid 1 and Hybrid 3 (age ten) suckers post-shearing, and Native 1 and Native 2 (age ten) suckers post-shearing.

Grouped sites	Number of plots	Tree characteristics	Mean	Standard Deviation	Coefficient of Variation (%)
Hybrid 2 and Hybrid 3 (pre-shear saplings)	41	Height (m)	4.54	1.44	32
		dbh (cm)	3.38	1.42	42
		Volume (dm^3)	3.35	3.41	102
Hybrid 2 and Hybrid 3 (pre-shear suckers)	37	Height (m)	2.89	1.28	44
		dbh (cm)	1.60	0.87	54
		Volume (dm^3)	0.66	0.93	141
Hybrid 1 and Hybrid 3 (post-shear suckers)	53	Height (m)	9.19	2.18	24
		dbh (cm)	6.05	2.02	33
		Volume (dm^3)	16.26	13.82	85
Native 1 and Native 2 (post-shear suckers)	10	Height (m)	5.93	1.41	24
		dbh (cm)	3.60	1.00	28
		Volume (dm^3)	4.02	2.35	58

3.3.3 Volume and biomass production

Stand volume and biomass production were compared on the ten-year-old native (Native 1 and Native 2) and hybrid (Hybrid 1 and Hybrid 3) aspen sucker stands. Stand volume was substantially higher on both hybrid aspen sites relative to the native aspen stands (Figure 3.1). The Hybrid 3 site had the highest stand volume (mean = 63.94) which was more than 4.2 times that of the Native 2 site. Individual tree biomass in the hybrid sites was more than 3.6 times (mean = 14.43) greater than in the native sites (3.97) of the same age. Stand level biomass production was calculated using the mean stems per hectare on the native and hybrid aspen sucker sites. The hybrid aspen sites produced substantially more biomass per hectare than the native aspen sites of the same age (Figure 3.2). The Hybrid 3 site averaged nearly 2.8 times (mean = 86.66) as much biomass/ha as the Native 2 site (mean = 31.34).

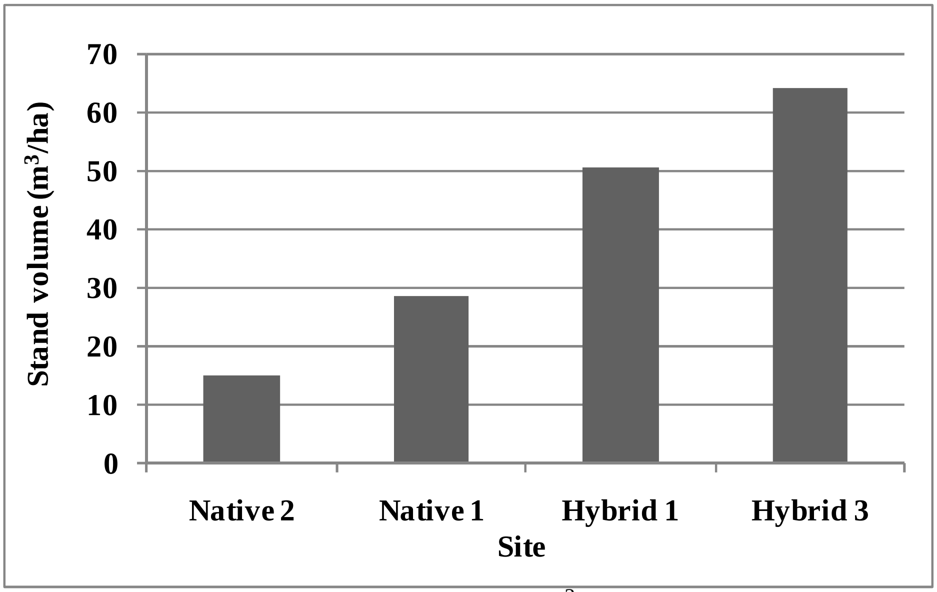

Figure 3.1 Estimated total stand volume (m^3/ha) from 0.15 m stump to tip of all trees ≥ 0.30 m tall for post-shear ten-year-old native and hybrid aspen stands. Native 1 and 2 (site index = 21.6), Hybrid 1 (site index = 24.4), and Hybrid 3 (site index = 21.3).

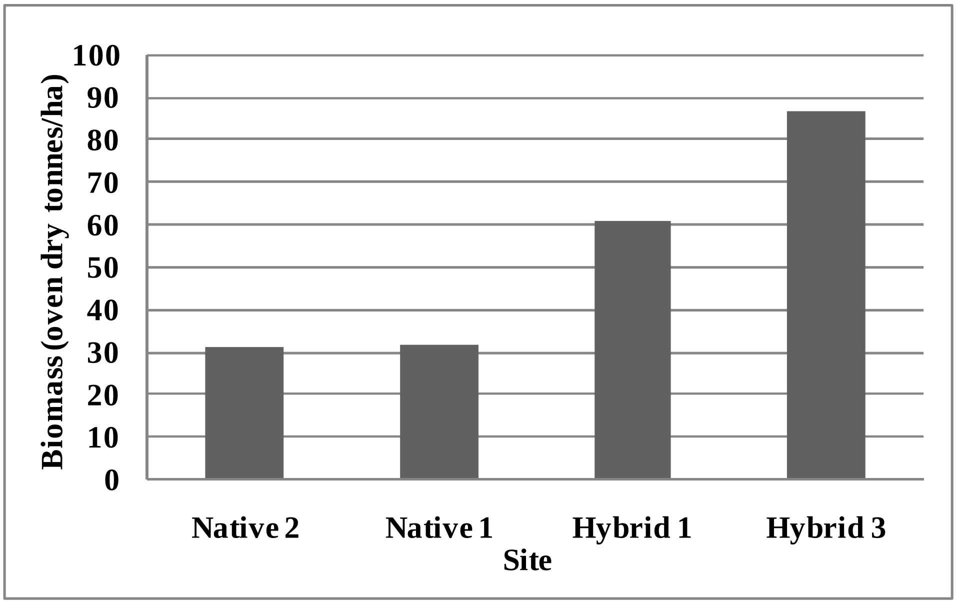

Figure 3.2 Estimated total aboveground biomass (oven dry tonnes/ha) for trees 2.5 cm dbh and larger for post-shear ten-year-old native and hybrid aspen stands. Native 1 and 2 (site index = 21.6), Hybrid 1 (site index = 24.4), and Hybrid 3 (site index = 21.3).

3.4 Discussion

Renewed interest in the use of woody biomass for energy has created an opportunity for the development of silvicultural systems that can produce high levels of biomass over shorter rotations than traditional approaches to plantation management. This is one of only a few studies examining hybrid aspen sapling and sucker response to shearing treatments at an operational scale. The results suggest that hybrid aspen yield can be substantially higher than the already high-yielding parental species and that shearing is a viable option for increasing stand density on marginally stocked sites.

3.4.1 Stem density

Shearing hybrid aspen sapling and sucker stands ranging in age from seven to thirteen years substantially increased initial hybrid aspen sucker density on all sites (Table 3.2). These results are consistent with a similar shearing study conducted in native aspen stands with similar site index in north central Minnesota (Perala 1983). Hybrid aspen sucker density increased on the Hybrid 1 site from years one to four following the shearing treatment and subsequently began to decrease. The initial increase is not surprising, given native aspen suckers typically continue to appear in the first two years after treatment (Brown and DeByle 1987). Thereafter, self-thinning begins and continues throughout the life of the stand (Peet and Christensen 1987). Pre-shear sucker density in young hybrid aspen stands may also contribute to post-shear regeneration success. In this study, the Hybrid 1 site had the highest mean sucker density and the lowest mean sapling density of the three hybrid aspen sites at the time of shearing (age thirteen) and produced more than two times as many suckers/ha in the first year post-shearing as the next highest hybrid aspen site (Table 3.2). The higher pre-shear sucker densities would generally be a sign of higher root densities, which would translate into higher post-shear sucker densities (Graham et al. 1963, Frey et al. 2003).

There are several other factors which may also have contributed to the differences in sucker density after shearing. These include pre-shear stand age, family variation, differences in site index, soil moisture, soil temperature, and varying levels of harvesting and traffic impacts to existing root systems (Li and Wu 1997, Frey et al. 2003). Despite large differences in stand density before and after shearing and extensive self-thinning in the ten years post shearing, all three hybrid aspen stands exceeded full stocking recommendations (Perala 1983) for native aspen in the last sample period. These findings suggest that shearing is a viable option for improving stocking in young hybrid aspen stands.

3.4.2 Tree characteristics

Pre-shear seven- and eight-year-old hybrid aspen saplings and suckers were compared on the same sites (Hybrid 3 and Hybrid 2). The planted hybrid aspen saplings were substantially larger than the hybrid aspen suckers (Table 3.3). This is not surprising since the planted hybrid aspen seedlings must establish strong root systems before producing suckers. This may occur in as little as three years under ideal conditions but when herbivory and vegetative competition exists, the process may take much longer.

A comparison of pre-shear seven- and eight-year-old hybrid aspen saplings to post-shear ten-year-old native aspen suckers revealed that the native aspen stands had slightly higher mean diameter and volume and markedly higher mean height (Table 3.3). This may be due to age but may also be the result of competition for light with other aspen suckers. As aspen stem density increases, light levels decrease, forcing suckers to forage for light and allocate resources to height growth rather than diameter growth (Comeau 2002). In the pre-shear hybrid aspen stands, stem density was relatively low, with stems scattered individually or in pockets, so competition for light was not as severe as it typically is in native aspen sucker stands of similar age. These height characteristics are consistent with other studies, which have found that planted hybrid aspen saplings require a period of adaption and root expansion before vigorous height and diameter growth can begin (Luoranen et al. 2006). Even with this adaption period, the pre-shear seven- and eight-year-old hybrid aspen saplings in this study had similar mean diameter and volume per tree as the post-shear ten-year-old native aspen suckers. The height and diameter characteristics from the hybrid aspen saplings in this study are also consistent with hybrid aspen studies in Sweden, Finland, and Estonia (Yu 2001, Rytter 2006, Tullus et al. 2007). As with differences in sucker density, differences in stand age, family, and microclimate may also be contributing to these trends in height characteristics (Barnes 1966).

Post-shear native aspen sucker heights and diameters were also compared to post-shear hybrid aspen sucker characteristics in stands of the same age. The-ten-year-old hybrid aspen stands were substantially taller and had higher mean diameter than the native aspen sucker stands (Table 3.3). Hybrid aspen suckers were more than 3 m taller and 2 cm in diameter larger at breast height than native aspen suckers of the same age. These large increases point to hybrid vigor, although it must be noted that stand density was higher in the native aspen stands. The increased height and diameter growth of the hybrid suckers resulted in a concomitant increase in individual stem volume. Mean hybrid aspen stem volume in the ten-year-old stands was more than 4.0 times higher than native stems of the same age. The improved volume is not surprising given the diameter and height characteristics and results from similar studies in the Midwest and Scandinavia. For example, a study in Iowa found that the mean annual increment (MAI) of hybrid aspen stems at age ten was approximately 1.42 dm^3 which is consistent with results from the post-shear hybrid aspen sites (MAI = 1.62) in this study (Hall et al 1982). Similarly, Yu et al. (2001) found that mean estimated stem volume of five-year-old hybrid aspen was 3.9 times that of native European aspen (*P. tremula*) in Finland. That said, microclimatic variation and differences in stand density and site index across the sites may have contributed to the large difference in tree volume.

3.4.3 Stand volume, biomass production, and carbon storage

Stand volume varied substantially across the four ten-year-old stands. This was likely due to differences in stand density and individual tree volume across the four sites. The hybrid aspen stands (Hybrid 1 and Hybrid 3) had much lower stem density (Table 3.2) than the native aspen sites (Native 1 and Native 2) but substantially higher individual tree volumes (Table 3.3), resulting in markedly higher stand volume estimates (Figure 3.1).

The ten-year-old hybrid aspen stands produced more than twice as much biomass per hectare as the ten-year-old native aspen stands (Figure 3.2). These yields are consistent to those found in hybrid aspen stands in Sweden (Rytter and Stener 2003, Rytter 2006), Germany (Liesebach et al. 1999), and Iowa (Hall et al. 1982), and native aspen stands in north central Minnesota (Perala 1983). Nonetheless, these findings should be interpreted with caution. In particular, the biomass equation used to calculate oven dry weight of above-ground woody material was developed through a large-scale, nationwide meta-analysis (Jenkins et al. 2003). While this equation is useful, stand-specific, local or regional equations would be more appropriate to accurately estimate woody biomass production.

Much of the renewed interest in hybrid aspen and other fast-growing tree species has revolved around renewable fuels and the potential fossil fuel offsets of using woody biomass for energy (Kauter et al. 2003); however, there is also potential for substantial belowground carbon storage with the expansion of living root systems. The root systems of most tree species die when the above-ground portion of the tree is removed (King et al.

2007); however, the root system of most *Populus* spp. in the section *Populus* (formerly Leuce) (Eckenwalder 1996) remains active for decades, and in some cases, centuries after the above-ground portion of the tree is killed (Kemperman and Barnes 1976). These belowground structures provide the carbohydrates necessary for root suckers to establish after harvest (Barnes 1966, Frey et al. 2003). As root suckers grow, they contribute to the expansion of the belowground clonal root system and the process is repeated after each harvest or stand-replacing disturbance. While some root die-off occurs following major disturbance, most of the belowground structures continue to grow and can extend many hectares in some parts of the aspen range though most are restricted to less than a hectare in size (Kemperman and Barnes 1976). With the establishment of short-rotation hybrid aspen plantations comes the establishment of long-term belowground carbon storage structures. These structures immediately begin storing carbon and continue to expand with each subsequent above-ground disturbance. As such, the use of hybrid aspen systems for the production of biofuel feedstocks may also offer an opportunity to increase belowground carbon storage and enhance the carbon offset potential of these areas.

3.4.4 Silvicultural methods for stand development

The establishment of high density, large area plantations is currently constrained by limited quantities of high genetic quality planting stock, both seedling and clonal origin. Silvicultural approaches to overcome planting stock availability and high establishment costs have been examined on an operational scale. A recommended practice includes: 1) controlling competing vegetation before planting 250-370 well-distributed trees per hectare, 2) protecting planted seedlings from herbivory, 3) growing the trees for six to eight years, allowing root systems to sufficiently develop and occupy much of the area between trees, and 4) cutting these sapling-size trees and producing a sucker stand. This approach adds four to six years to the first rotation (suckers reach heights of uncut stems very quickly). Another establishment method calls for interplanting hybrid aspen in every sixth row in larch (*Larix* spp.) plantations where pulpwood clearcut harvests are planned for age 20 to 25. These approaches have the advantage of low establishment costs and the deployment of rapid growing feedstock of limited availability.

3.4.5 Harvesting considerations

Seasonality, cutting height, and equipment limitations are three important harvesting considerations in short-rotation coppice systems. Harvest timing is important given the interactions between apical dominance and seasonal fluctuations in carbohydrate reserves (Bates et al. 1993, Bell et al. 1999, Frey 2003). In most native aspen stands in the Lake States regeneration success is not a concern so timing of the harvest, at least for the sake of regeneration, is not a major consideration (Mundell et al. 2008). In contrast, on sites where hybrid aspen is deliberately planted at low densities with the intention of increasing stem density through shearing, harvesting should be done during the dormant season to maximize sucker response. In addition, the height at which stems are harvested may be important when considering regeneration in young native and hybrid aspen stands. In particular, Bell et al. (1999) found that increasing the cutting height in young native aspen stands reduced sucker production and stem mortality and increased sprouts and overall sprout height. Finally, equipment capable of efficiently harvesting large quantities of small diameter, high density material on uneven terrain is not common in the Lake States. This type of equipment would be necessary for large-scale short-rotation systems to be cost-effective in the region.

3.5 Conclusion

This study, although somewhat limited statistically, demonstrates that the use of hybrid aspen in combination with shearing treatments provides an effective and straightforward approach for generating woody biomass for energy relative to native *Populus* species. The use of coppice silvicultural systems with this forest type also provides an opportunity to increase belowground carbon storage, due in large part to the presence and expansion of clonal root systems over time in these areas. These increases in carbon are particularly important to consider in areas where hybrid poplar is being planted on former agricultural lands, as this will allow for the proper accounting of greenhouse gas offsets related to feedstock production within biofuels life cycle analyses (Searchinger et al. 2008). As such, future work examining the patterns of belowground carbon storage in these areas will be critical for generating reliable estimates of the impacts of these practices on regional patterns of carbon sequestration.

Chapter 4

Model framework for the assessment of carbon flows associated with the procurement and utilization of harvest residues for energy

Forest-derived biomass is a renewable fuel that can be procured locally from a variety of sources such as forest harvest residues and small diameter material from early silvicultural treatments. Energy generation from renewable feedstocks like forest biomass may alter the carbon balance in comparison to the use of fossil fuels like coal or natural gas. Carbon flows associated with the extraction and utilization of fossil fuels for the production of energy are well documented, while those associated with forest biomass are not. This study presents a model framework for estimating harvest residue availability and carbon flows associated with the extraction, transport, and utilization of the biomass residues in a proposed 26-megawatt bioenergy facility in northern Minnesota. Model results suggest the facility would emit 0.28 tonnes of CO_2/MWh based on a 100-year planning horizon. While this estimate is markedly lower than direct CO_2 emissions reported for fossil fuels (i.e., exclusive of extraction, refinement, and transport emissions), it suggests there are carbon costs associated with the utilization of forest-derived biomass residues for energy production.

4.1 Introduction

Utilization of renewable resources for energy has increased substantially in the United States over the last several decades. These increases have been driven, in large part, by energy policy aimed at reducing dependence on foreign oil, boosting economic development, and curbing fossil fuel emissions (Gau et al. 2007, McCarl and Boadu 2009). Early bioenergy legislation was initiated at the national level (Energy Policy Act of 1992, Federal Energy Policy Act of 2005, Energy Independence and Security Act of 2007). In recent years, state governments have passed laws mandating further reductions in energy consumption and greenhouse gas emissions, and increases in energy conservation and use of renewables (Becker et al. 2010a). In 2007, the Minnesota Legislature passed the Next Generation Energy Act aimed at bolstering investments in renewable power, increasing energy conservation, and decreasing the state's contribution to global warming (Minnesota Statute 216C.0. 2007). In response to the legislation, a Minnesota energy provider proposed the development of a 26-megawatt (MW) woody biomass generation facility as part of its plan to develop additional renewable energy resources and offset carbon emissions from their coal-fired facilities. The company initiated a comprehensive review detailing forest fuel supply, procurement, and project engineering as well as an assessment of carbon flows associated with the extraction and utilization of harvest residues (tops and limbs and small diameter material) to inform decision making on investments in renewable energy.

There have been a number of studies that have used existing forest inventory databases to estimate biomass availability and carbon stocks (Cost et al. 1990, Birdsey 1992, Brown et al. 1997, Ney et al. 2002). Those studies have focused on a variety of spatial scales and have used a variety of techniques to estimate biomass and carbon flows. This study builds on previous work by combining several methods into a framework designed to estimate carbon flows associated with the extraction, transport, and utilization of forest harvest residues for energy over a multi-year planning horizon. The objectives were to 1) characterize biomass availability over time and by forest type, 2) estimate carbon stocks in the study area over different planning horizons, 3) develop a model to estimate the flow of carbon associated with forest harvesting, transportation of raw material to the energy facility, and carbon flux associated with forest management in the study area (with and without the proposed facility), and 4) provide a standardized estimate of carbon emissions for northern forests associated with the production of energy from forest harvest residues for comparison to other fuel sources and to inform renewable energy project development and policy.

4.2 Methods

4.2.1 Definitions

There are many definitions of woody biomass. For the purposes of this study, we followed the Minnesota Forest Resources Council (2007) definition which includes: snags, tops and limbs, coarse woody debris, stumps (not included in this analysis), under-sized stems, and brush. Estimates in this analysis are based on live tree data >2.54 cm in diameter at breast height so the results reflect live biomass and forest harvest residues in the aforementioned categories.

4.2.2 Study area

The study area includes forest resources located within a 100-mile radius of the proposed bioenergy facility in Minnesota. The area represents 7,859,660 acres of timberland in northeast Minnesota and 1,417,649 acres in northwest Wisconsin for a total of 9,277,309 acres (Table 4.1). There are several forest types within the study area but only a few species and forest types dominate. The aspen forest, which is dominated by *Populus tremuloides* (Michx.) and to a lesser extent *P. grandidentata* (Michx.) occupies more than 36 percent of the study area or 3,209,306 acres (Table 1). Balsam fir (*Abies* *balsamea* (L.) Mill.) represents about 7 percent of the aspen forest type volume in the study area, and paper birch (*Betula papyrifera* Marsh.) represents about 6 percent. The spruce forest type, which is dominated by *Picea mariana* ((Mill.) Britton, Sterns and Poggenb.) and to a lesser extent *P. glauca* ((Moench) Voss), represents nearly 12 percent of the productive forestland in the study area and paper birch accounts for nearly 8 percent (Table 4.1). Northern white-cedar (*Thuja occidentalis*) is included in the total acreage but not in the analysis due to the relatively small proportion of cedar harvested annually. The average live biomass per acre for each age class and forest type in the study area is listed in Table 4.2. The maple-basswood and northern hardwood forest types have the greatest volume per acre across all age classes (live trees >2.54 cm diameter), while tamarack and spruce have the lowest biomass per acre. This is not surprising as the majority of tamarack and spruce stands within the study area are growing on low to moderately productive sites. Due to limited information on harvest levels and transportation networks for the Wisconsin portion of the study area, information from Minnesota was extrapolated to develop the carbon assessment.

4.2.3 Data sources

Data for this study were collected from a variety of sources. The geographic location of the facility was used to retrieve specific USDA Forest Service Forest Inventory and Analysis (FIA) field plot locations within the study area using Forest Inventory Mapmaker Version 3.0 (Miles 2008). The FIA Data Mart (2008) was then used to retrieve empirical data on the 4,716 FIA plots within the study area.

Table 4.1 Forest types by acres and stand age class for the project study area.

Age Class	Jack pine	Red pine	Balsam fir	Spruce	Tamarack	N. white-cedar	Bottomland hardwoods
0-10	9,067	21,642	24,563	32,087	21,275	2,188	26,298
11-20	25,955	36,236	53,321	39,790	22,225	2,349	11,398
21-30	43,344	46,787	28,101	50,107	24,521	7,627	25,837
31-40	52,881	48,213	34,689	71,585	38,916	6,940	19,172
41-50	18,096	46,900	58,880	160,567	56,239	13,143	28,374
51-60	16,799	37,874	55,171	160,850	46,797	28,220	83,935
61-70	17,343	32,484	26,395	195,300	88,756	26,328	89,013
71-80	21,111	16,898	14,574	148,696	68,490	36,026	114,271
81-90	15,492	13,149	9,463	96,546	51,076	34,472	68,947
91-100	0	8,825	13,801	56,068	35,835	35,213	21,378
100+	0	15,157	12,184	144,885	48,531	189,435	106,354
Total	220,088	324,165	331,142	1,156,481	502,661	381,941	594,977

Age Class	Northern hardwoods	Maple-basswood	Aspen	Paper birch	Balsam poplar	Other	Total
0-10	33,352	27,079	618,543	49,668	36,624	235,467	1,137,853
11-20	10,506	2,987	467,036	48,896	27,418	58,652	806,769
21-30	25,410	6,078	376,090	33,657	17,993	27,664	713,216
31-40	29,584	12,857	310,188	31,547	26,705	59,064	742,341
41-50	19,006	23,032	402,221	49,094	27,972	77,736	981,260
51-60	67,430	29,808	397,732	151,218	32,268	80,845	1,188,947
61-70	99,199	83,271	350,585	168,699	24,451	105,681	1,307,505
71-80	64,369	82,998	200,964	110,330	18,699	82,190	979,616
81-90	49,372	52,274	56,896	42,515	6,080	53,503	549,785
91-100	15,239	7,061	17,674	33,031	2,334	24,901	271,360
100+	13,692	11,185	11,377	12,760	3,182	29,915	598,657
Total	427,159	338,630	3,209,306	731,415	223,726	835,618	9,277,309

This information was used to characterize the forest resources in the study area and as model inputs for projecting carbon flows over the 100-year time horizon.

Estimates of logging residues (tops and limbs and small diameter material) were taken from the Minnesota Department of Natural Resources (MNDNR 2006) Minnesota Logged Area Residue Analysis. The volume of coarse and fine woody debris reported for each forest type were used in conjunction with volume-to-mass estimates reported in the MN DNR (1981) Timber Scaling Manual to derive forest type-specific residual biomass values. The residual biomass values were then applied to the average live harvestable biomass per acre for each species and forest type to determine the proportion of roundwood left as residual biomass (Table 4. 3).

Table 4.2 Average biomass per acre (tonnes) by stand age class and forest type for the project study area.

Age Class	Red pine	Jack pine	Balsam fir	Spruce	Tamarack	Bottomland hardwoods
0-10	5.76	5.20	11.01	7.6	10.41	11.86
11-20	17.14	10.04	14.28	8.2	5.96	10.27
21-30	30.19	15.62	13.94	12.6	8.81	12.75
31-40	34.49	17.65	19.63	13.7	11.67	8.48
41-50	38.42	23.08	21.73	16.8	10.45	19.09
51-60	37.18	23.37	19.13	19.3	16.99	25.85
61-70	48.79	32.47	17.32	18.1	19.67	31.74
71-80	64.91	34.53	18.16	19.8	16.62	32.32
81-90	49.35	26.04	21.56	19.2	19.71	39.84
91-100	49.85	31.04	20.19	12.6	18.51	41.18
100+	52.38	35.44	15.63	13.9	18.64	36.47

Age Class	Northern hardwoods	Maple-basswood	Aspen	Paper birch	Balsam poplar	Other
0-10	13.33	20.14	8.48	13.06	10.0	9.07
11-20	15.16	25.29	14.74	13.44	11.9	10.22
21-30	17.89	48.85	19.56	12.40	23.5	15.94
31-40	28.18	36.84	24.95	28.32	24.4	22.01
41-50	45.87	38.12	33.40	27.18	31.2	31.57
51-60	44.84	55.95	34.66	36.95	32.1	33.74
61-70	44.75	53.34	39.90	37.89	28.3	29.64
71-80	47.07	59.76	43.08	35.72	28.5	47.10
81-90	55.69	64.93	40.06	42.55	46.2	45.06
91-100	46.82	56.58	56.28	42.26	--	40.98
100+	56.20	60.84	41.34	39.35	--	54.38

Information on the extraction and processing of logging slash was compiled from existing literature (Sturos et al. 1983, Brinker et al. 2002) modeled for Lake States operations, as well as from personal communications with logging professionals operating within the study area (Tables 4.4 and 4.5). Due to a dearth of information on harvesting efficiency for the forest types found in the study area, a conservative estimate of 50 percent of the total residual biomass available was assumed to be extractable. This estimate is based on recommendations from the MN DNR (2006) Logged Area Residue Analysis, as well as from work in whole-tree harvested black spruce stands in Ontario (FPInnovations 2008 presentation). The remaining 50 percent left on site exceeds the 33 percent recommended by the Minnesota Forest Resources Council (2007) to sustain soil productivity, biological diversity, and wildlife habitat on forest lands. This recommendation assumes that 20 percent of the fine woody debris (tops and limbs) is intentionally retained with an additional 10 to 15 percent retention achieved by incidental breakage during removal. These assumptions will vary depending on the type of equipment used, silvicultural prescription, season of harvest, and forest type and condition, and so the more conservative estimate of 50 percent was assumed.

Table 4.3 Estimated annual roundwood and residual biomass harvest targets for the study area based on the average statewide harvest levels by forest type over the last 5 years.

Species	% Residual	% Roundwood	Roundwood biomass	Residual biomass
Jack pine	0.17	0.83	129,150	26,571
Red pine	0.10	0.90	77,163	8,334
Balsam fir	0.26	0.74	106,666	36,767
Spruce	0.24	0.76	27,525	8,649
Tamarack	0.28	0.72	115,088	45,434
Bottomland hardwoods	0.24	0.76	25,430	7,833
Northern hardwoods	0.19	0.81	30,169	6,972
Maple-basswood	0.15	0.85	38,740	6,708
Aspen	0.15	0.85	903,195	163,544
Paper birch	0.22	0.78	200,098	55,964
Balsam poplar	0.25	0.75	42,649	14,021
Other	0.20	0.80	34,016	8,742
Total			1,729,889	389,539

Table 4.4 Equipment productivity for harvesting sub-merchantable biomass less than 12.7 cm dbh (based on Sturos et al. 1983).

Equipment	Horsepower	PMH	Machine Rate (tonnes/PMH)	gal/hp-hr	gal/PMH	gal/tonne chips	kg C/gal	kg C/tonne chips	Tonnes C/Tonne chips
Drott 40 LC Feller/buncher	250	62.0	23.86	0.0263	6.583	0.276	10.391	2.8664	0.0022
740 John Deere Skidder	180	29.1	50.84	0.02800	5.040	0.099	10.391	1.0301	0.0008
Morbark 22-in Chipper	630	27.8	53.22	0.03492	22.00	0.413	10.391	4.2955	0.0034

Table 4.5 Equipment productivity for harvesting logging residues – tops and limbs (based on Sturos et al. 1983).

Equipment	Horsepower	PMH	Machine Rate (tonnes/PMH)	gal/hp-hr	gal/PMH	gal/tonne chips	kg C/gal	kg C/tonne chips	Tonnes C/Tonne chips
Drott 40 LC Feller/buncher	250	94.8	31.07	0.0263	6.583	0.212	10.391	2.2013	0.0017
740 John Deere Skidder	180	92.1	31.98	0.02800	5.040	0.158	10.391	1.6375	0.0013
Morbark 22-in Chipper	630	61.6	47.82	0.03492	22.00	0.460	10.391	4.7806	0.0037

To characterize transportation routes and estimate carbon emissions for transport of biomass to the bioenergy facility, a GIS layer was created with FIA plot coordinates and the bioenergy facility coordinates overlaid on a roads layer allowing for calculating transportation distances to and from various harvesting sites. To estimate annual carbon emissions resulting from transport of harvest residuals, an average roundtrip transportation distance (270 kilometers) was determined by calculating the average distance of FIA plot locations from the bioenergy facility. The roundtrip haul estimate was used in conjunction with fuel consumption data (2.02 kilometers per liter) for log trucks and chip vans (collected from a survey of logging professionals in the study area) and the annual biomass utilization target (251,336 green tonnes) at the bioenergy facility to estimate transport emissions.

4.2.4 Carbon flow model

The carbon flow model developed for this study is a series of spreadsheet models linked together to estimate current and future carbon stocks on timberlands within the study area, as well as carbon flows associated with forest management activities. The following sections provide a description of each spreadsheet model, key inputs, and assumptions.

4.2.5 Forest age class change model

The model form chosen to estimate forest type change is based on the idea of area control in forest management, where specification of the acreage harvested annually is used to manage (or control) the development of the forest over time (Buongiorno and

Gilless 2003). The model, through the description of changes in forest type acreage by age class, is then used to relate the impacts associated with forest harvesting, transportation of raw material to the bioenergy facility, and estimated net carbon flows associated with forest management in the study area.

A forest age class change model (Domke and Ek 2009) was developed using FIA inventory data (2003-2007) to grow timberland acres over a 100-year time horizon. This model portioned the acres within the study area into 10-year age classes and each year, 10 percent of those acres were assumed to move into the next age class. Acres at the end of the final age class (110 yrs) were assumed to die and return to the 0-10 year age class in each forest type in order to create a closed system with no loss of acres over the 100-year planning horizon.

Rotation length and harvest intensity varied by forest type. Baseline rotation ages were based on recommendations in the Forest Development Manual (MN DNR 1997) and adjusted based on professional judgment and current harvesting conditions reported in Minnesota's Forest Resources report (MN DNR 2007). Harvest intensity, based on the volume harvested annually, was proportionally rated based on Minnesota statewide harvest levels reported in Minnesota's Forest Resources report (MN DNR 2007). Table 4.6 displays the estimated volume harvested by forest type within the study area. Since harvest levels vary from year to year, the average statewide harvest over the most recent five year period (2001-2005) was used as the starting volume cut by forest type. In reality, some (but not all) stands are cut at or near the rotation age. In fact, harvesting continues throughout all harvestable age classes until all available stands are harvested, die, or succeed to another forest type. The harvested acres in each age class were multiplied by the average biomass derived from FIA data for each 10-year age class (Table 4.2). The biomass estimate for each age class was based on the oven-dry weight of all live stems in each age class >2.54 cm diameter at breast height. All biomass values were then converted to carbon using an equation developed by Birdsey (1992) that assumes the dry mass of wood is approximately 50 percent carbon.

Table 4.6 Proportion of the Minnesota statewide harvest volume within the study area used to define harvest targets (study area ODT).

Forest type	Proportion of statewide harvest	Proportion of forest type in study area	Study area volume (cords)[1]	Study area ODT (tonnes)
Jack pine	0.082	0.501	149,263	155,721
Red pine	0.043	0.525	81,951	85,496
Spruce	0.054	0.768	150,579	143,433
Tamarack	0.017	0.517	31,900	36,174
Balsam fir	0.053	0.800	153,866	160,522
Bottomland hardwoods	0.014	0.577	29,334	33,264
Northern hardwoods	0.018	0.456	29,775	37,141
Maple-basswood	0.034	0.335	41,317	45,448
Aspen	0.510	0.557	1,031,472	1,066,739
Paper birch	0.089	0.699	225,807	256,061
Balsam poplar	0.030	0.478	52,057	56,670
Other	0.053	0.196	37,706	42,758

[1] Based on the 5-year average Minnesota statewide harvest level 3,630,000 cords.

4.3 Carbon sequestration

Carbon sequestration rates are a function of tree growth and thus, yield, which generally follows a nonlinear, asymptotic pattern with age. To account for this, yield was modeled using FIA data and the Carbon Online Estimator (COLEv2.0 USDA FS 2005). Sensitivity analysis showed that yield curves for all forest types in the study area (FIA analysis) and Minnesota (COLE) change their slope at approximately age 40, which allowed us to derive two separate carbon sequestration rates for stands < 40 years of age and stands ≥ 40 years of age using linear regression. Figure 4.1 illustrates the sensitivity analysis that was run for the aspen forest type and all other forest types in the study area to approximate the age at which the rate of carbon sequestration changes.

For forest stands ≥ 40 years of age, carbon accumulation rates were estimated simultaneously by two methods that were then compared for consistency. The first method used empirical information from the FIA analysis within the study area and the other used data generated by the COLE for all forest types in Minnesota. Regression analysis was used in both methods to determine the rate of carbon accrual by stand age, based on rotation length. Due to the high levels of uncertainty associated with temporal changes in other carbon pools, we assumed that all other pools of carbon in the ecosystem did not vary over the 100-year projections.

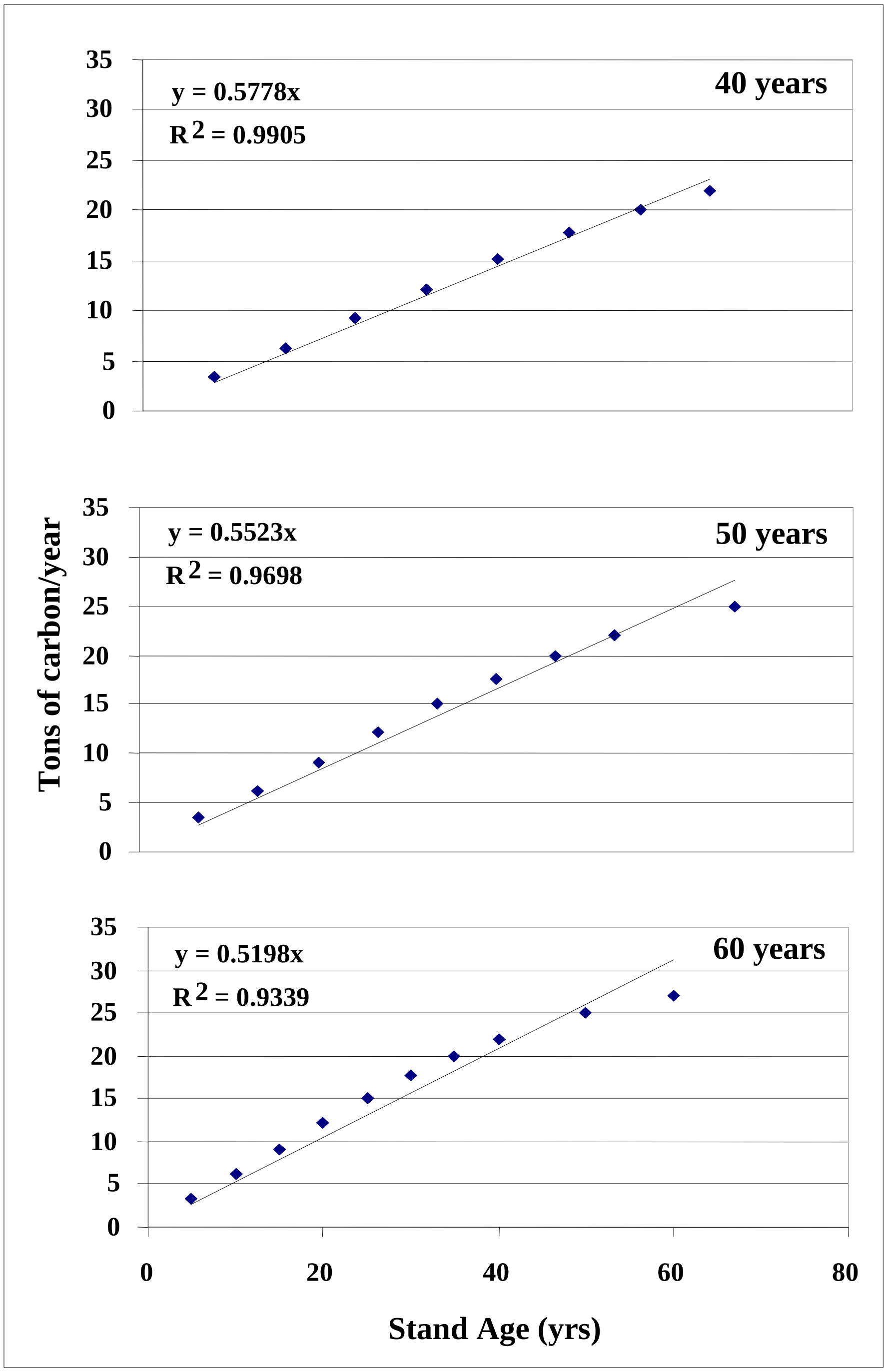

Figure 4.1 Sensitivity analysis using COLE data and linear regression to determine the age at which carbon sequestration begins to change for the aspen forest type.

Moreover, the change in total carbon (C) in accumulating wood vastly outweighs other changes —thus, for purposes of this assessment, we treated wood as the sole variable estimated. Both methods provided estimates of annual carbon sequestered per acre. The empirically derived estimate was 0.70 tonnes C/acre/year (Figure 4.2) and the modeled rate was 0.58 tonnes C/acre/year (Figure 4.3). These estimates were averaged to provide a parsimonious sequestration rate for stands <40 years of age for all forest types within the study area. For stands ≥40 years, a carbon accumulation rate of 0.11 tonnes C/acre/year was derived from linear regression analysis using COLE for the all forest types in Minnesota (Figure 4.4). FIA data were not used for the ≥40 year analysis due to the lack of data and large variability for many forest types. Table 4.7 lists the carbon sequestration estimates per acre per year for the forest types in the study area.

4.3.1 Decay emissions

To determine the carbon emissions associated with the decay of forest biomass left following harvest, the following equation was used:

$$D_t = D_0 e^{(-kt)}$$

where D_t is the annual decomposition, D_0 is the residual biomass produced each year, t is the time of decomposition (years), and k is the decomposition constant. Decomposition constants were used from existing literature when available or were derived from published values used for other species in this study (Table 4.8). The annual decomposition values were integrated over the entire harvest area and time until nearly all biomass was decomposed (< 0.1 tonnes). In all cases, this required more than 100 years. Consequently, the biomass decay estimates for each planning horizon were reported along with the range in time necessary for nearly complete decomposition (< 0.1 tonnes). Note that only the extractable biomass, which was assumed to be 50 percent of the available harvest residuals, was included in the analysis since the remaining biomass would be left on site with or without the proposed bioenergy project.

4.3.2 Harvesting emissions

The model harvest system is described as a conventional, whole-tree operation that processes the tree and residual biomass (limbs and tops) at the harvest landing. Once at the landing, the biomass is processed using either a chipper or grinder, then transported to the mill in a chip van. Forest type mix, size class, and wood quality, as well as site conditions, management and regeneration objectives, are key determinants of recoverable biomass volume on a given harvest site, which may vary greatly depending on these factors.

Equipment horsepower, delay-free productive machine hours (PMH), and diesel fuel consumption rates for each piece of equipment were used to calculate the carbon dioxide (CO_2) emitted per tonne of wood chips processed. Carbon emissions conversion factors for diesel fuel were used from the Climate Registry (2005).

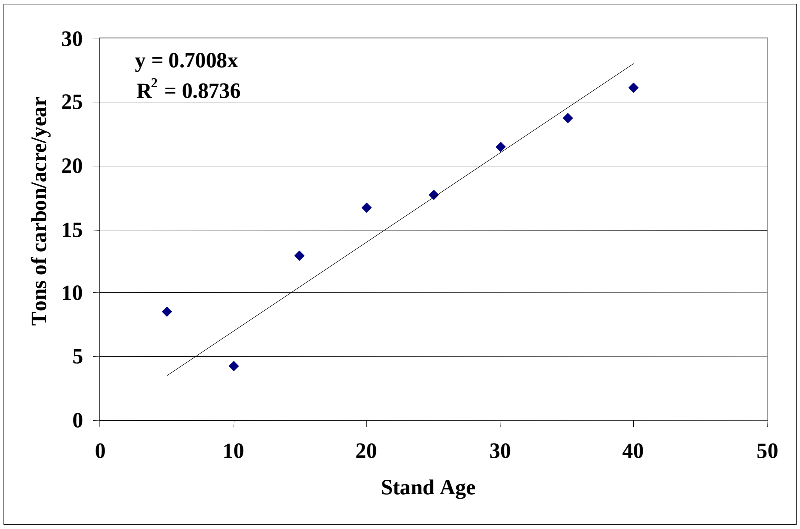

Figure 4.2 Regression analysis (empirical) used to estimate annual sequestration/acres for stands < 40 years of age for the aspen forest type within the study area.

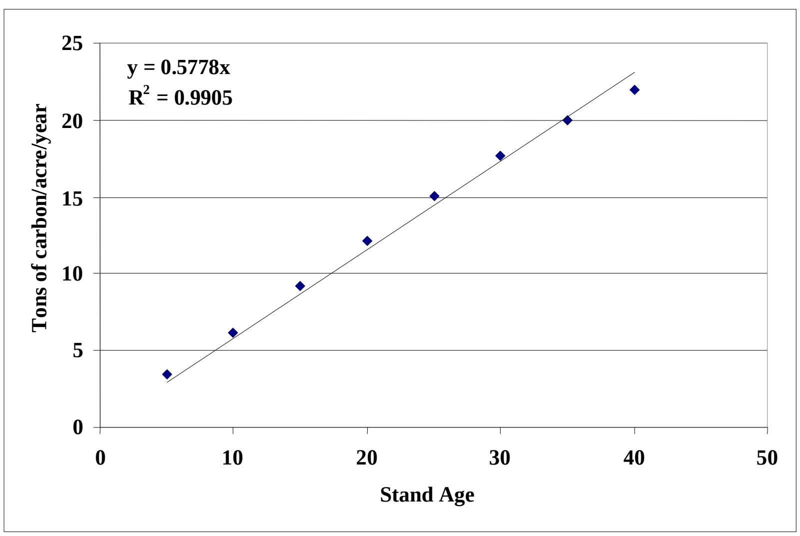

Figure 4.3 Regression analysis using COLE—generated carbon stocks to calculate the annual carbon sequestration/acre for stands < 40 years of age for the aspen forest type in Minnesota.

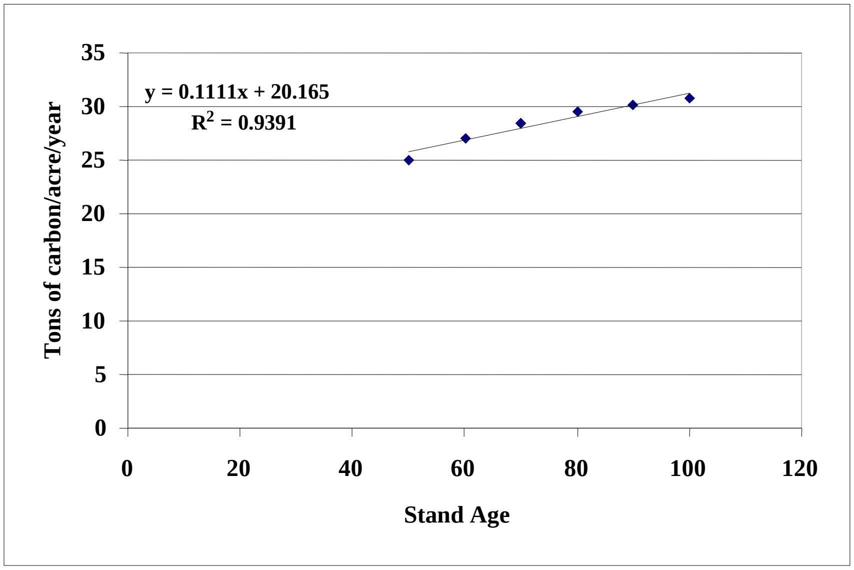

Figure 4.4 Regression analysis using COLE - generated carbon stocks to calculate the annual carbon sequestration/acre for stands > 40 years of age for the aspen forest type in Minnesota.

Table 4.7 Annual carbon sequestration/acre (tonnes C) for the forest types in the study area calculated using FIA and COLE data and linear regression.

	< 40 years			≥ 40 years
	------------------Data Source------------------			Data Source
Forest Type	**COLE**	**FIA**	**Average**	**COLE**
Jack pine	0.52	0.53	0.53	0.08
Red pine	0.75	0.97	0.86	0.10
Balsam fir	0.69	0.56	0.63	0.05
Spruce	0.53	0.41	0.47	0.11
Tamarack	0.48	0.32	0.40	0.14
Bottomland hardwoods	0.46	0.37	0.42	0.18
Northern hardwoods	0.90	0.75	0.83	0.07
Maple-basswood	0.77	0.50	0.64	0.14
Aspen	0.58	0.70	0.64	0.11
Paper birch	0.51	0.66	0.59	0.09
Balsam poplar	0.52	0.72	0.62	0.05
Other	0.64	0.60	0.62	0.16

The whole-tree harvest system was modeled as a Drott 40 LC Feller/Buncher, John Deere 740 Skidder, and a Morbark self-loading chipper. Productivity and horsepower ratings used for each piece of equipment are reported in Tables4. 4 and 4.5 based on studies of comparable harvest conditions, forest types, and size classes in the Lake States (Sturos et al. 1983, Gingas and Favreua 1996). Fuel consumption rates per PMH were calculated based on estimates from Brinker et al. (2002).

Table 4.8 Decay constants used to calculate the annual decomposition of extractable biomass within the study area.

Forest type	Decay rate (K)	Source
Aspen	0.080	Alban and Pastor 1993
Balsam poplar	0.080	Assumed K as aspen in Alban and Pastor 1993
Paper birch	0.068	Harmon et al. 2000
Maple-basswood	0.045	MacMillian 1988
Northern hardwood	0.096	Arthur et al. 1993
Bottomland hardwood	0.089	Chueng and Brown 1995
Other	0.076	Mean of all published values in this table
Balsam fir	0.011	Lambert et al. 1980
Jack pine	0.042	Alban and Pastor 1993
Red pine	0.055	Alban and Pastor 1993
Spruce	0.071	Alban and Pastor 1993
Tamarack	0.045	Mean of published conifer values in this table

Total productivity was modeled for both small diameter material (< 12.7 dbh) and chips from slash generated from the harvest of roundwood (≥ 12.7 cm dbh). Productivity and fuel usage is affected by the size of machines used, horsepower rating, and equipment specifications. Other factors affecting productivity include tree species, size, taper, and site operability, which may vary greatly from one location to another. The productivity equations used in this study are proxies and do not reflect the full range of possible harvest systems in use.

4.3.3 Transportation emissions

The emissions from transporting biomass residue to the bioenergy facility were estimated using data from a recent survey of logging companies operating within the study area. Companies were asked to provide average annual fuel consumption for chip hauling equipment. This information was used in conjunction with the average FIA plot distance estimated using GIS to calculate transport emissions based on a 22.7-tonne (25-short ton) load from within the appropriate fuel procurement radius. Road type was used to calculate speeds and associated fuel usage and emissions, which were then scaled up for all biomass processed to determine the annual CO_2 emissions of transporting residue to the bioenergy facility.

4.3.4 Carbon flow model assumptions

Due to the nature of the carbon flow analysis, it was necessary to make several assumptions. Below is a detailed list of key assumptions with associated values used to develop the estimates:

- The total timberland area within the study area remained fixed at 9,277,309 acres and all acres assigned to each forest type (Table 1) remained fixed with no conversion to other types or addition from changing land use.
- The annual biomass necessary to fuel the bioenergy facility was assumed to be 145,652 oven-dry tonnes (ODT) for annual generation of 182,208 MWh.

- The model assumes that there are no disturbances (e.g., insects, disease, fire) other than forest management to set back stand ages. One tenth of the acres in each age class moved to the next age class annually unless harvested.
- Rotation lengths assigned to each forest type in the model were based on the Forest Development Manual (MN DNR 1997) and professional judgment.
- Harvest intensity measured as the percent cut in each age class for each forest type was adjusted based on rotation length and the proportion of the total harvest assigned to each forest type. Table 3 was used to fine tune each forest type-specific model to reflect the volume removed annually over the last five years reported in the Minnesota's Forest Resources report (MN DNR 2007).
- FIA plot coordinates were used to represent harvest locations when calculating average harvest site distance.
- All slash and small diameter material available for use from the site is included in estimates of total available biomass. The analysis does not consider economic feasibility of removal or optimization by species type and landowner.
- Carbon contributions from the manufacturing and delivery of the harvesting equipment were not included in the modeled system, nor were the carbon contribution from the construction of highways to access forests and the bioenergy facility.
- Loss from chipping is estimated from values obtained by Stokes and Watson (1991). For clean and dirty chips, flail chain loss is estimated at 15.10 percent of total chips. For clean chips only, screening reject is 4.90 percent.

- Average fuel (wood) moisture content was assumed to be 42 percent.
- Conversion from carbon to carbon dioxide (CO_2) was based on the atomic mass of C and CO_2, where one carbon atom is 12 u and one oxygen atom is 16 u. Therefore, the conversion factor used was 44/12 or 3.67.

4.3.5 Trace gas assumptions

In addition to the carbon dioxide (CO_2) flows associated with the removal and/or decay of woody biomass, other gases -- namely nitrous oxide (N_2O) and methane (CH_4) -- have the potential to alter the overall carbon budget. To compare these gases with CO_2 emissions, the Global Warming Potential (GWP) of each gas was used. GWP is intended to be a quantified measure of the globally averaged radiative forcing impacts of a particular greenhouse gas (EPA 2002). GWP is expressed on a relative basis using carbon dioxide as the reference gas to which all other greenhouse gases are compared. While GWP values are a useful measure for estimating the relative impacts of emissions and reductions of different gases, they typically have an uncertainty of approximately ±35 percent (EPA 2002). Nitrous oxide has a GWP 310 times that of CO_2 so even minor emissions or reductions of this gas have significant consequences.

There are many anthropogenic sources of nitrous oxide, including fertilization in agricultural situations, combustion of fossil fuels, wastewater treatment, and waste combustion; however, the only source potentially relevant to this study is biomass burning. Minimal information exists for quantities of logging residues subjected to open field burning, prescribed burning, or wildland fire, and their effective N_2O emissions. N_2O emission factors for boiler combustion of woody biomass vary between EPA and

IPCC publications from 0.013 lbs/MMBtu (0.03 tonnes CO_2e/MWh) to 0.009 lbs/MMBtu (0.02 tonnes CO_2e/MWh), respectively (EPA 1995, Gomez et al. 2006). Due to the uncertainty of N_2O production in forests, the potential contribution of N_2O was not included in the carbon flow model.

Methane, which is primarily produced through anaerobic decomposition of organic matter, has a GWP 21 times that of CO_2 (EPA 2002). Anthropogenic sources of CH_4 include agricultural processes such as rice cultivation, enteric fermentation in livestock, and the decomposition of animal wastes. Methane is also emitted during incomplete fossil fuel combustion, and during the production and distribution of natural gas. The primary methane source of concern in this study is the decomposition of organic matter (leaf material, tops, and limbs from harvest and natural mortality and breakage) on or near the forest floor (Megonigal and Guenther 2008, Mukhin and Voronin 2009). The methane emitted through litter decomposition may be offset, in part, by soil bacteria (methanotrophs) which use methane as a source of carbon through methane oxidation (Adamsen and King 1993, Schnell and King 1994, Sitaula et al. 1995). Due to the uncertainty of CH_4 production in forests following harvest, the potential contribution of CH_4 was not included in the LCA.

4.4 Results

4.4.1 Biomass availability

Under current levels of forest management and commercial harvesting, the proposed bioenergy facility would utilize approximately 145,652 ODT of woody biomass annually to generate 182,208 MWh per year of electricity (operating at 80 percent capacity factor). Based on the study assumptions, sufficient biomass is available within the assumed procurement radius of approximately 160 km (Table 4.3).

4.4.2 Carbon stocks

Table 4.9 lists the current estimated harvest acres and carbon stocks expressed as M (million) tonnes of carbon dioxide (CO_2). The average annual harvest of roundwood in the study area is 3.46 M tonnes CO_2 and the average annual residual is 0.60 M tonnes CO_2. Of the 0.596 M tonnes of residual biomass produced from the annual harvest, 50 percent is considered operationally feasible to remove, which results in an average annual extractable biomass availability in the study area of 0.30 M tonnes CO_2.

Table 4.10 lists the total harvest acres and carbon stocks over the 100-year planning period within the study area.. The total harvest of roundwood over the 100-year planning horizon (based on the current average statewide harvest level) is 349.63 M tonnes CO_2 and the total extractable biomass produced from harvesting over the 100-year period is 30.07 M tonnes CO_2.

4.4.3 Carbon sequestration

The carbon sequestration estimates for the forest types within the study area are listed in Table 4.11. Average annual carbon sequestration is 2.55 M tonnes CO_2. The total carbon sequestration over the 100-year planning period for each forest type is 254.99 M tonnes CO_2.

Table 4.9 Estimated annual carbon stocks (CO_2) by forest type within the study area.

Forest type	Total acres 0-100+ (years)	Annual harvest (acres)	Annual harvest	Annual extractable residue removed
			--------- (M tonnes CO_2) ---------	
Aspen	3,209,306	41,274	2.247	0.172
B. poplar	223,726	2,068	0.086	0.011
Paper birch	731,415	5,310	0.289	0.032
Maple-basswood	338,630	1,488	0.042	0.003
Northern hardwood	427,159	2,464	0.056	0.005
Bottomland hardwood	594,977	3,358	0.042	0.005
Other	835,618	5,276	0.088	0.010
Balsam fir	331,142	4,288	0.117	0.015
Jack pine	220,088	2,092	0.087	0.007
Red pine	324,165	2,062	0.183	0.009
Spruce	1,156,481	6,725	0.176	0.021
Tamarack	502,661	4,421	0.048	0.007
TOTAL	8,895,368	80,827	3.462	0.298

Table 4.10 Estimated total carbon stocks (CO_2) by forest type within the study area.

Forest type	Total acres 0-100+ (years)	Annual harvest (acres)	Annual harvest	Extractable residue removed
			-------- (M tonnes CO_2) --------	
Aspen	3,209,306	4,168,642	226.993	17.400
B. poplar	223,726	208,895	8.692	1.075
Paper birch	731,415	536,328	29.194	3.190
Maple-basswood	338,630	150,313	4.205	0.310
Northern hardwood	427,159	248,853	5.629	0.528
Bottomland hardwood	594,977	339,206	4.203	0.495
Other	835,618	532,879	8.863	1.029
Balsam fir	331,142	433,096	11.861	1.520
Jack pine	220,088	211,342	8.831	0.753
Red pine	324,165	208,310	18.494	0.901
Spruce	1,156,481	679,181	17.781	2.126
Tamarack	502,661	446,478	4.881	0.740
TOTAL	8,895,368	8,163,524	349.627	30.069

Table 4.11 Estimated carbon (M tonnes CO_2) sequestered annually and over the 100-year planning period within the study area.

Forest type	**Annual sequestration**	**Total Sequestration**
	--------- **(M tonnes CO_2)**	--------
Aspen	0.340	34.008
B. poplar	0.060	6.031
Paper birch	0.139	13.946
Maple-basswood	0.196	19.621
Northern hardwood	0.267	26.691
Bottomland hardwood	0.316	31.563
Other	0.440	44.007
Balsam fir	0.106	10.629
Jack pine	0.039	3.916
Red pine	0.075	7.461
Spruce	0.388	38.762
Tamarack	0.184	18.354
TOTAL	**2.550**	**254.989**

4.4.4 Decay emissions

The average annual emissions from decay of extractable biomass, which would otherwise be utilized in the bioenergy facility, are listed in Table 4.12. Estimated annual decay emissions are 0.23 M tonnes CO_2. Total decay emissions from extractable residual biomass (50 percent of the total available biomass) left on harvest sites over the 100-year planning period are 22.71 M tonnes CO_2 (Table 4.12).

Table 4.12 Estimated carbon (M tonnes of CO2) emitted through decomposition annually and over the 100-year planning horizon from extractable biomass left on the harvest site for each forest type.

Forest type	Annual Decay	Total Decay
	------ (M tonnes CO_2) ------	
Aspen	0.136	13.617
B. poplar	0.008	0.844
Paper birch	0.025	2.496
Maple-basswood	0.002	0.223
Northern hardwood	0.004	0.430
Bottomland hardwood	0.004	0.396
Other	0.008	0.796
Balsam fir	0.006	0.552
Jack pine	0.005	0.524
Red pine	0.007	0.667
Spruce	0.016	1.645
Tamarack	0.005	0.520
TOTAL	**0.227**	**22.710**

4.4.5 Harvesting and transport emissions

Harvesting and transport emissions represent a small proportion of the collective carbon flux within the study area when comparing with-project and without-project scenarios. However, the harvest and transport emissions in the with-project scenario are not offset by any emissions in the without-project scenario and contribute a net positive CO_2 to the results. Table 4.13 lists the estimated annual and cumulative harvest and transport emissions to extract and haul 145,652 ODT of woody biomass to the bioenergy facility. The average annual harvest emissions are 0.0062 M tonnes CO_2, while the annual transport emissions are 0.004 M tonnes of CO_2 and the cumulative (100-years) harvest and transport emissions are 0.62 M tonnes CO_2 and 0.408 M tonnes CO_2, respectively.

Table 4.13 Esimtated annual and cumulative (100-year) carbon (M tonnes of CO_2) emissions from harvesting and transport for each forest type within the study area.

Forest type	Annual Emissions		Cumulative Emissions	
	Harvesting	Transport	Harvesting	Transport
	------------------ (M tonnes CO_2) -------------------			
Aspen	0.00360	0.00240	0.3600	0.2360
B. poplar	0.00020	0.00010	0.0220	0.0150
Paper birch	0.00070	0.00040	0.0660	0.0430
Maple-basswood	0.00010	0.00000	0.0060	0.0040
Northern hardwood	0.00010	0.00010	0.0110	0.0070
Bottomland hardwood	0.00010	0.00010	0.0100	0.0070
Other	0.00020	0.00010	0.0210	0.0140
Balsam fir	0.00030	0.00020	0.0310	0.0210
Jack pine	0.00020	0.00010	0.0160	0.0100
Red pine	0.00020	0.00010	0.0190	0.0120
Spruce	0.00040	0.00030	0.0440	0.0290
Tamarack	0.00020	0.00010	0.0150	0.0100
TOTAL	0.00620	0.00410	0.6220	0.4080

4.4.6 Carbon flow summary

Estimated annual carbon flows with and without the bioenergy facility are listed in Table 4.14. With the proposed facility, the annual CO_2 emissions are estimated to be 0.28 M tonnes. This estimate includes carbon stock removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the facility. Without the proposed facility, the annual decay of CO_2 from the extractable biomass left on the harvest site is estimated to be 0.23 M tonnes. The difference between the with- and without-project scenarios is 0.05 M tonnes of CO_2. With an estimated production of 182,208 MWh/yr, the difference in with- and without-project scenarios is a net positive production of 0.003 tonnes of CO_2/MWh.

Cumulative (100-years) carbon flow with and without the bioenergy facility is described in Table 4.15. With the proposed facility the total CO_2 emissions area estimated to be 27.76 M tonnes. This estimate includes carbon stock removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the facility. Without the proposed, facility the total estimated decay in CO_2 from the extractable biomass left on the harvest site is 22.71 M tonnes. The difference between the with- and without-project scenarios is 5.05 M tonnes of CO_2. With an estimated production of 182,208 MWh/yr (18.22 M MWh/100yrs), the difference in with- and without-project scenarios is a net positive production of 0.28 tonnes of CO_2/MWh.

4.5 Discussion

4.5.1 Carbon flows

The total carbon flows over the 100-year planning horizon with and without the bioenergy project were developed under a number of assumptions listed above. Figure 4.5 illustrates the net carbon inputs and outputs described in the study. With the proposed facility, the total estimated CO_2 emitted over the life of the project is 27.76 M tonnes. This estimate includes carbon stock removed from the harvest site, carbon emissions from extracting biomass, and carbon emissions from transport to and from the proposed bioenergy facility. Without the proposed facility, the total CO_2 emissions from decomposition of extractable biomass left on the harvest site is estimated to be 22.71 M tonnes. With the 100-year production of 18.22 M MWh of electricity generated from the bioenergy facility, the resulting CO_2 per unit production is 0.28 tonnes CO_2/MWh. This value would most likely be reduced to just emissions from harvesting and transport

(0.057 tonnes of CO_2e/MWh) if the planning horizon were extended to allow the accumulated biomass over the 100-year planning period (which would otherwise be utilized in the bioenergy facility) to decompose completely. Complete decomposition would likely take approximately 250 to 350 years for most species, based on the exponential decay rates used in this study. Importantly, decay processes vary substantially by material size, woody decay class, location, climate, and species. Thus, the decay rate model and associated rate estimates should be used with caution.

The carbon flow values presented here would also change under different methane and nitrous oxide emissions assumptions. As previously stated, our examination suggested that trace gas fluxes would be very small in the context of this study. Consequently, analysis was limited to the CO_2 emissions and did not include secondary gases. Future studies of this type would benefit from further research on trace gas emissions from decomposition of logging residues. Should methane from biomass decomposition prove to be present in traceable quantities, utilization for energy could substantially decrease the net carbon footprint of biomass energy facilities.

Table 4.14 Estimated annual carbon stock changes with and without the proposed bioenergy facility. Extractable residue removed values have been adjusted based on total plant capacity (ca. 89 percent of total extractable residue available).

	--------------------------With project--------------------------				--Without project--		
	Extractable Residue Removed	Emissions Harvesting	Emissions Transport	Total	Decay	Total	Difference
Forest type	---(M tonnes CO_2)---						
Aspen	0.155	0.004	0.002	0.161	0.136	0.136	0.024
B. poplar	0.01	0	0	0.01	0.008	0.008	0.001
Paper birch	0.028	0.001	0	0.029	0.025	0.025	0.004
Maple-basswood	0.003	0	0	0.003	0.002	0.002	0.001
Northern hardwood	0.005	0	0	0.005	0.004	0.004	0.001
Bottomland hardwood	0.004	0	0	0.005	0.004	0.004	0.001
Other	0.009	0	0	0.01	0.008	0.008	0.002
Balsam fir	0.014	0	0	0.014	0.006	0.006	0.009
Jack pine	0.007	0	0	0.007	0.005	0.005	0.002
Red pine	0.008	0	0	0.008	0.007	0.007	0.002
Spruce	0.019	0	0	0.02	0.016	0.016	0.003
Tamarack	0.007	0	0	0.007	0.005	0.005	0.002
TOTAL	0.267	0.006	0.004	0.278	0.227	0.227	0.050

Table 4.15 Estimated cumulative (100-years) carbon stock changes with and without theproposed bioenergy facility. Extractable residue removed values have been adjusted based on total plant capacity (ca. 89 percent of total extractable residue available).

	With project				Without project		
	Extractable Residue Removed	Emissions Harvesting	Emissions Transport	Total	Decay	Total	Difference
Forest type	(M tonnes CO_2)						
Aspen	15.466	0.36	0.236	16.063	13.617	13.617	2.446
B. poplar	0.956	0.022	0.015	0.993	0.844	0.844	0.149
Paper birch	2.836	0.066	0.043	2.945	2.496	2.496	0.449
Maple-basswood	0.276	0.006	0.004	0.286	0.223	0.223	0.064
Northern hardwood	0.47	0.011	0.007	0.488	0.43	0.43	0.058
Bottomland hardwood	0.44	0.01	0.007	0.457	0.396	0.396	0.061
Other	0.915	0.021	0.014	0.95	0.796	0.796	0.154
Balsam fir	1.351	0.031	0.021	1.403	0.552	0.552	0.851
Jack pine	0.67	0.016	0.01	0.696	0.524	0.524	0.172
Red pine	0.801	0.019	0.012	0.832	0.667	0.667	0.165
Spruce	1.889	0.044	0.029	1.962	1.645	1.645	0.318
Tamarack	0.657	0.015	0.01	0.683	0.52	0.52	0.163
TOTAL	26.727	0.622	0.408	27.758	22.71	22.71	5.047

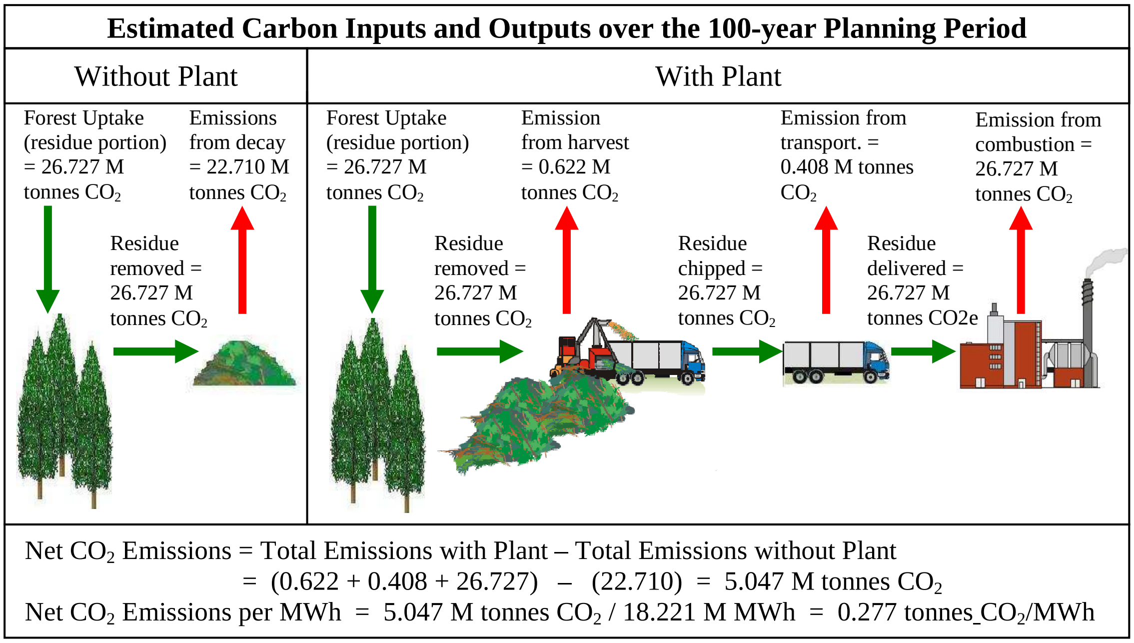

Figure 4.5 Estimated carbon inputs and outputs (M tonnes of CO_2/MWh) over the 100-year planning period for the proposed bioenergy facility.

4.5.2 Improvements in forest management and harvesting

Currently, widespread removal of logging residues is limited in part by available harvesting equipment, fuel costs, roundwood market fluctuations, and landowner interests. Importantly, the biomass estimates in this study do not fully incorporate these economic or social constraints. To compensate for limited supplies, the supply distance may need to be expanded or management practices intensified to increase biomass availability.

Increases in yields, and thus, sequestration, are possible with intensified forest stand management. With investment in combinations of practices such as using improved planting stock, improved site preparation, and early vegetation management including early and commercial thinnings, the yields per acre as shown in Table 2 for the forest types may be increased substantially (Ek 2007). In this study, trials indicated yields were also sensitive to rotation length. Shortening rotations tended to increase supply over the 100-year planning horizon, particularly for the short lived species (i.e., aspen, paper birch, jack pine). This investment could increase the rate of carbon sequestration as well as overall storage potential of our short-lived forests and also result in more residual biomass available for utilization. Advancements in harvesting technologies have created opportunities for harvesting small diameter material. Should this trend continue, the interest in thinnings and logging residues may also increase.

4.5.3 Comparisons to fossil fuels

The proposed bioenergy facility in northern Minnesota is estimated to emit 0.28 tonnes of CO_2/MWh based on the 100-year planning horizon. Removing the harvesting and transport emissions from the overall estimate provides a direct emissions estimate of 0.22 tonnes of CO_2/MWh. This estimate can be compared to direct emissions reported for fossil fuels in the Electric Power Annual (2007). Direct emissions (exclusive of extraction, refinement, and transport) for coal steam turbines are approximately 1.00 tonnes CO_2/MWh. Natural gas combustion turbines emit approximately 0.60 tonnes CO_2/MWh, and natural gas combined cycle emissions are approximately 0.40 tonnes CO_2/MWh. With an estimated production of 182,208 MWh/yr, converting from coal steam turbines to forest residues for energy production would reduce emissions by approximately 142,122 tonnes CO_2 annually. In regions where forest-derived biomass is available, using harvest residues for energy generation may provide a viable option for reducing greenhouse gas emissions and dependence on fossil fuels for energy.

4.6 Conclusions

As electrical utilities weigh renewable energy options to meet state and federal energy targets, they will need a methodology for comparing existing emissions with renewable alternatives. This study provides a methodology for estimating the carbon flows associated with the procurement and utilization of forest *harvest residues* for energy. The results suggest there is a carbon cost associated with the utilization of harvest residues for energy, however when weighed against direct emissions (exclusive of extraction, refinement, and transport) from fossil fuels used in energy production, the costs are comparatively small.

We relied on a number of assumptions in this study in order to generate results useful for comparison to fossil fuel emissions associated with energy production. Our analysis compared CO_2 emissions over a 100-year time horizon. While this time period may make sense from a forest management perspective, it may not be the most appropriate time period to account for carbon flows in forests from a policy or atmospheric science perspective. The atmospheric lifetime of CO_2 is estimated to range from 5-200 years, depending on the rate of sequestration by different processes (IPCC 2007). This variability in CO_2 sequestration is evident even within this study. Young red pine stands (< 40 years), for example, would sequester, on average, more than twice the carbon per acre per year that young tamarack or bottomland hardwood stands would within the study area (Table 4.7). Given this variability, it would be useful to provide carbon flow estimates over multiple temporal scales, ranging from much shorter, to potentially longer than the 100-year time horizon used in this study. This approach would provide a more complete picture of the potential carbon benefits or consequences of biomass utilization for energy in the near and long term.

Chapter 5

Model development for rapid estimation of forest-derived biomass availability

Renewed interest in woody biomass for energy has created a need for rapid estimation of roundwood and harvest residues available for utilization. The Forest Age Class Change Simulator (FACCS) is a spreadsheet-based computational tool designed to estimate current and future biomass availability under user-defined management scenarios and harvest intensities. FACCS relies on existing data sources and forest management information to produce forest type specific biomass estimates over multiple spatial and temporal scales. In this chapter details on the development of the base model are described, along with examples of recent model applications and future uses.

5.1 Introduction

Recent state energy legislation and pending federal action has led to renewed interest in the use of forest-derived biomass for energy production (Becker et al. 2010a). In 2007, the Minnesota Legislature made a commitment to increase renewable energy production and conservation and decrease greenhouse gas emissions by passing the Next Generation Energy Act (Minnesota Statue 216C.0 2007). This prompted energy providers to begin looking at renewable resource options such as forest-derived biomass and, particularly, harvest residues as potential fuel sources. Since 2002, utilization of harvest residues (small diameter stems and tops and limbs) has increased more than fivefold, from 15,400 oven-dry tons (ODT) to an estimated 100,000 ODT (MNDNR 2004, MNDNR 2010a). Increased utilization has been driven, in large part, by the development of new bioenergy projects and retrofitted co-generation technologies at existing forest products facilities. There are currently 43 woody biomass-related energy facilities in

Minnesota, which produce approximately 1.3 percent of the state’s total energy (EIA 2008, MNDNR 2010b).

Rapid expansion of forest-derived bioenergy markets has created concerns over the current and future physical, social, economic, and environmental availability of roundwood and residual biomass in the state. While current physical availability can be estimated using data from the USDA Forest Service Inventory and Analysis (FIA) program, that data does not reflect harvesting limitations, annual harvest levels, management practices, or market pressures. A variety of computer models and decision support systems have been developed to accommodate a complex array of decisions and constraints associated with the production, procurement, and utilization of forest-derived biomass (Mitchell 2000, Freppaz et al. 2004, Frombo et al. 2009). These tools have been very useful for informing bioenergy project proposals and supply assessments but are often limiting due to data requirements, modeling expertise, and software adaptability.

FACCS is a spreadsheet-based tool designed to estimate current and future biomass availability and carbon stocks under a variety of user-defined scenarios. It was developed as the main component of a design support system to aid a bioenergy developer interested in biomass availability and carbon flows associated with the use of harvest residues for energy. It was designed using a popular spreadsheet platform familiar to a wide range of potential users. This format also allows for adaption to a broad range of biomass supply and carbon flow applications. This chapter describes the development of the FACCS base model and provides examples of recent model applications and future uses.

5.2 Model development

FACCS was originally conceived to aid in estimating carbon flows associated with the procurement, transport, and utilization of harvest residues for energy (Domke et al. 2008a). The tool was developed using a widely accepted spreadsheet platform so that a variety of components could be built into the biomass base model and for accessibility by those familiar with the spreadsheet software.

5.2.1 User interface

The base model consists of a customized lookup table which is populated with forest type specific inventory information (e.g., area, yield, harvest levels) for the area of interest, along with the user-defined harvest rate table. The lookup table allows the user to populate a single sheet with information that is linked to a large number of user-defined forest type sheets. Forest type sheets rely on spreadsheet functions as well as equations and data from the lookup table sheet to generate biomass estimates by area and age class over a user-defined time horizon. A variety of other information derived from the biomass estimates such as carbon stocks can be generated in the forest type sheets, if desired. Results in each forest type sheet are summarized and linked to a single output sheet and annual harvest estimates are linked back to the harvest rate table within the lookup table sheet to allow the user to match specified harvest targets for the area of interest. The output sheet utilizes a series of pivot-table tools to generate tables and figures describing the biomass or carbon attributes of interest.

5.2.2 Data inputs

The FACCS base model relies on a small number of core inputs which can be generated from forest inventory data or adapted from published sources. The model was originally designed to operate using FIA data summarized by forest type for the geographic region of interest. The primary inputs include forest land area, biomass yield, and harvest level targets. Forest land area can be generated for specific geographic locations, political regions (i.e., counties and states), or other attributes through FIA data (USDA Forest Service FIA DataMart Version 4.0) queries or by using the online FIA Retrieval System (EVALIDator Version 4.01), other inventory systems or published sources. Forest land area information is summarized by forest type and 10-year age class in a lookup table (Table 5.1) and linked to the appropriate forest type sheet. Biomass yield information can be generated in a similar manner on a per unit area basis (e.g., hectare or acre) by forest type and age class for the user-defined area or attribute (e.g., site index class) and regression techniques can be employed to establish continuous values for all age classes in the model. The biomass equations developed for each forest type are included in the lookup table and linked to individual age classes in the forest type sheets to generate biomass per unit area estimates. Alternatively, published biomass equations (Jenkins et al. 2003) can be used to generate estimates by forest type if inventory information does not include yield estimates for the area or attribute of interest. Biomass per unit area estimates in each forest type sheet are then multiplied by the estimated area in the matching age class to generate biomass estimates by forest type and age class for the area of interest. Harvest level targets in the model are based on average statewide harvest levels by forest type. Harvest level targets at smaller spatial scales are proportionally adjusted, based on the area and volume of the area of interest. Table 5.2 summarizes Minnesota statewide harvest level targets based on 10-year average harvest levels published by the MN DNR (2009). Additional information such as mortality factors, residual biomass proportions, and management alternatives (e.g., shortened or extended rotations, early stand treatments) can also be incorporated, if desired.

Table 5.1 Forest type area (acres) by age class for Minnesota FIA Survey Units 1-3[1].

Age Class	White-red-jack pine	Spruce-fir	Oak-pine	Oak-hickory	Elm-ash-cottonwood	Maple-beech-birch	Aspen-birch
0-10	53,818	90,524	19,086	110,089	60,438	120,802	874,022
11-20	73,969	143,681	23,470	49,342	32,130	52,841	784,396
21-30	142,509	183,014	25,834	53,680	56,409	44,377	694,483
31-40	120,667	223,174	17,971	72,956	81,630	35,301	580,081
41-50	116,381	391,367	25,293	206,598	114,007	90,482	662,170
51-60	82,864	432,816	46,942	251,997	200,262	131,939	747,010
61-70	71,457	461,762	35,237	310,352	217,846	243,447	765,427
71-80	64,158	379,067	19,973	294,178	175,626	193,993	438,626
81-90	59,377	283,891	16,798	215,901	121,474	174,928	163,001
91-100	21,507	228,504	2,902	116,204	74,653	63,017	63,147
100+	33,838	641,271	17,062	127,407	132,952	66,105	49,012

[1] **Survey Unit 1:** Carlton, Cook, Koochiching, Lake, St. Louis, **Survey Unit 2:** Aitkin, Becker, Beltrami, Cass, Clearwater, Crow Wing, Hubbard, Itasca, Lake of the Woods, Mahnomen, Roseau, Wadena, **Survey Unit 3:** Anoka, Benton Carver, Chisago, Dakota, Douglas, Fillmore, Goodhue, Hennepin, Houston, Isanti, Kanabec, Le Sueur, Mille Lacs, Morrison, Olmsted, Otter Tail, Pine, Ramsey, Rice, Scott, Sherburne, Streans, Todd, Wabasha, Washington, Winona, Wright Counties.

Table 5.2 Harvest level targets by forest type based on the 10-year average statewide harvest levels in Minnesota (Becker et al. 2010a).

Forest Type	Proportion of statewide harvest	Estimated harvest (cords)	ODT/cord	Estimated ODT
White-red/jack pine	0.123	433,337	1.158	501,631
Spruce/fir	0.129	455,342	1.116	508,300
Oak/pine	0.008	27,532	1.259	34,671
Oak/hickory	0.037	132,354	1.375	181,987
Elm/ash/cottonwood	0.017	60,351	1.250	75,438
Maple/beech/birch	0.051	179,820	1.225	220,300
Aspen/birch	0.635	2,244,266	1.150	2,580,905
TOTAL	**1.000**	**3,533,000**		**4,103,232**

5.2.3 Area change matrix

Each forest type sheet includes an area change matrix, which is populated with information from the lookup table sheet and driven by a series of spreadsheet functions and user-defined harvest rates. The change matrix grows area over a user-defined time period. The area in each cell in the change matrix is linked to biomass equations in the lookup table sheet, which generate biomass estimates by age class and area over time.

The change matrix within each forest type sheet consists of rows which represent time (years) and columns which represent individual forest type age classes (years) (Table 5.3). The first row represents present day conditions (time = 0) and is populated with an array of forest type area values for each individual age class from the lookup table sheet. In the example in Table 5.3, the forest type currently (year = 2010) occupies 100 acres, all located in the year 1 age class. The total number of rows in the change matrix determines how long each forest type is grown. The modeled time horizon (growing period) in the example in Table 5.3 is 10 years (2010 to 2019). In the FACCS base model, growing periods (rows) range from 50-100 years and age classes (columns) range from 100-200 years. The first column (age class = 1) in the change matrix serves as the starting point for all acres removed from other cells due to harvesting. A spreadsheet function in column one compiles all harvested acres from the associated row. In the example in Table 5.3, five acres were harvested in 2013 in age class 4 and were reset to the first column, where they immediately begin growing. As acres are harvested over time, new cells are populated in the change matrix and multiple values will return to the first column at individual years. This is evident at years 2016 and 2019 in the example in Table 5.3.

Table 5.3 Example of the area change matrix within each forest type sheet.

Year	**Forest type age class (years)**										**Total Area (acres)**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	
2010	**100**	0	0	0	0	0	0	0	0	0	100
2011	0	**100**	0	0	0	0	0	0	0	0	100
2012	0	0	**100**	0	0	0	0	0	0	0	100
2013	**5**	0	0	**95**	0	0	0	0	0	0	100
2014	0	**5**	0	0	**95**	0	0	0	0	0	100
2015	0	0	**5**	0	0	**95**	0	0	0	0	100
2016	**6**	0	0	**4**	0	0	**90**	0	0	0	100
2017	0	**6**	0	0	**4**	0	0	**90**	0	0	100
2018	0	0	**6**	0	0	**4**	0	0	**90**	0	100
2019	**7**	0	0	**5**	0	0	**3**	0	0	**85**	100

The primary function moving the area values from one age class to the next over time begins in the second row and column of the change matrix and continues throughout the rectangular array of values. The basic function moves area values from one cell (year and age class) to the next, thereby growing the area over time. In the example in Table 5.3, cell 2010:1 represents 100 acres in year 2010 at age class 1. The basic function moves the value in cell 2010:1 to cell 2011:2 and so on through the matrix until a harvest occurs or the value reaches the end of the growing period in the matrix. The basic function is linked to the harvest rate table in the lookup table sheet, allowing the user to harvest a percentage of forest type area in a particular age class (based on established forest management guidelines). In the example in Table 5.3, five percent of the area (five acres) in age class 4 was harvested in 2013 and returned to the first column to begin growing again. The percent harvested in each age class is dependent on the harvest targets created in the lookup table sheet (Table 5.2). The function is wrapped in a conditional expression within each cell of the change matrix so that only available area can be harvested, preventing negative values in the model and maintaining a fixed number of acres in each row over time. The total area column in the example in Table 5.3 is the sum of all acres across age classes for the year of interest. This column serves as a guide to ensure the matrix is functioning properly as a closed system, with no change in total area from year to year, despite harvesting.

5.2.4 Biomass estimation

Biomass estimates and other user-defined attributes are developed from the area change matrix. In the FACCS base model, biomass equations from the lookup table sheet are linked to the age class values in the area change matrix within each forest type sheet. The biomass values at each age class are then multiplied by the area within each cell at that age class to generate total biomass estimates for a forest type, year, and age class. Harvested biomass is broken into two groups within the forest type sheets -- roundwood and residual. The average annual roundwood biomass harvest values are used to inform the user-defined harvest rates in the lookup table sheet. The residual material (tops and limbs) is a proportion of the roundwood biomass and a percentage of that material is deemed extractable, based on published information (MN DNR 2007).

5.2.5 Model assumptions

The FAACS base model relies on a few important assumptions: 1) forest type area is fixed with no conversion to other types or additions or losses due to land use change, 2) there are no disturbances (e.g., insects, disease or fire, except as these may be inherent in the yield by age class input) other than forest management to set back age classes—area continues to age unless harvested, 3) forest type area information is available for the area of interest by age class (Table 5.1), 4) empirical or estimated yield information is available for each forest type and age class, 5) harvest residue information is available for the modeled region, and 6) harvest intensity in the model is based on recent harvested volume data from the area of interest (Table 5.2).

5.3 Model applications

5.3.1 Assessment of carbon flows associated with the utilization of harvest residues for energy

FACCS was originally conceived to estimate residual biomass availability and the carbon flows associated with the procurement, transport and utilization of that material for energy production (Domke et al. 2008a). Once the FACCS base model was developed to estimate residual biomass available within the study area, it was expanded to estimate biomass decay rates (and associated CO_2 emissions) if the material were left in the forest rather than utilized for energy. It also estimated carbon sequestration of living biomass and carbon stocks of harvest residuals. Harvest and transport CO_2 emissions were also incorporated into the base model so carbon flows with and without utilization for energy could be compared. Early expansions of the base model maintained the overall integrity of the FACCS interface with a lookup table sheet, several forest type sheets, a transport and harvest sheet, and an output sheet.

5.3.2 Assessing forestation opportunities for carbon sequestration in Minnesota

The FACCS base model interface was adapted in a variety of ways in this study to accommodate the research needs. The goal of the project was to assess, under a variety of incentives, the carbon sequestration potential of forests on land that is currently in some alternative land use (Turner et al. 2010). The base model interface was changed so that the information originally in forest type sheets was housed within county-specific sheets with multiple change matrices for the different forest types within each county. Soil productivity information for each county was also incorporated into the model and biomass yield equations. Since the land under consideration was under some non-forest land use, all forest type area was phased into the model over a 10-year period to simulate actual establishment conditions (e.g., limitations in available planting stock, labor considerations, and managing competing vegetation). Finally, a carbon conversion matrix was developed and incorporated into the model to track carbon losses or gains associated with the conversion of non-forest area to different forest types.

5.3.3 2010 Outlook for Forest Biomass Availability in Minnesota

FACCS was adapted in this project to estimate residual biomass availability under a variety of management, utilization, marketing, and demand scenarios (Becker et al. 2010b). The base model was expanded over five spreadsheet workbooks, one for each major ownership type considered in the study (federal, state, county, industrial private, and non-industrial private). Each workbook included a series of lookup tables linked to individual county sheets from Minnesota and Wisconsin. Within each county-level sheet, seven area change matrices were built with accompanying biomass estimation tables which accommodated the wide array of management and utilization scenarios. Results from each sheet were linked to a single output sheet in each of the five ownership workbooks. An additional workbook was established to combine the output from the five ownership workbooks for use in developing tables and figures for reporting.

5.4 Discussion

Renewed interest in forest-derived biomass for energy has created a need for biomass estimation tools that provide energy utilities and land managers with reliable estimates of current and future biomass resources under a variety of management and market scenarios. A variety of computer models and decision support systems have been developed to accommodate stakeholder needs however they are often limiting due to data requirements, modeling expertise, and software adaptability. FACCS is a spreadsheet-based tool designed to estimate current and future biomass availability and carbon flows under a variety of user-defined scenarios. It was developed as the main component of a decision support system to aid a bioenergy developer interested in biomass availability and carbon flows associated with the use of harvest residues for energy. It has since been used on a number of other projects to estimate carbon sequestration and biomass availability over multiple spatial and temporal scales.

FACCS will continue to be refined to accommodate new projects. Recent improvements to the FIA database, for example, now allow for estimation of specific tree and forest type biomass and carbon attributes. The model is currently being adapted to estimate carbon stock changes on the Superior National Forest. This will require expanding FACCS to allow for forest type conversions over time. Mortality factors will also be built into the model to simulate natural mortality in combination with harvesting and forest type conversions.

FACCS relies on a number of important assumptions and user-defined inputs. Future versions of the model will incorporate Monte Carlo simulation methods to reduce the reliance on user-defined inputs, decrease uncertainty, and improve the overall validity of projections.

Chapter 6

Conclusion

The rise of the aspen forest type in the Lake States represents one of the largest human-induced vegetative conversions in history. Today, the aspen forest type is the most dominant group of species in the region and accounts for more than 41 percent of the total annual pulpwood harvest. A renewed interest in biomass for energy has created opportunities for all species in the region, but particularly the aspen species -- both native and hybrid -- due to their unique life history characteristics. This renewed interested in forest-derived biomass was prompted by state and federal energy legislation designed to increase energy conservation and decrease emissions of greenhouse gases from burning fossil fuels. As a result of this legislation, power utilities and land management agencies have becoming increasingly interested in forest-derived biomass availability and the carbon costs and benefits of using it in place of fossil fuels. This has created a demand for tools capable of using existing forest inventory information to estimate current and future biomass availability and carbon stocks over multiple spatial and temporal scales.

The goal of this dissertation was to contribute to the existing literature on aspen forest type trends and to present a methodology for estimating biomass availability and carbon flows associated with the extraction, transport, and utilization of biomass for energy. The three main chapters served to: describe the current status and trends of aspen research in the Lake States, helping to meet industry needs for information and technology transfer and identifying research gaps and areas for potential collaboration; assess aspen forest type changes in the region using USDA Forest Service FIA data; analyze biomass production potential in native and hybrid aspen communities following shearing treatments; and estimating biomass availability and carbon flows associated with the procurement and utilization of harvest residues for energy. Each main chapter in this dissertation was developed with a unique set of objectives without consideration for the others yet, when combined, all contribute to our broader understanding of the aspen resource.

The majority of the forest inventory information in chapter 2 has been updated with the latest FIA inventory data (2004-2008), so the tables and figures may differ from the original published document (Domke et al. 2008b). Stumpage price information was also updated for the three states and fluctuated considerably in the three years since the original figure was produced. The latest stumpage prices (2009) were nearly the same in all three states (~ $22.00/cord) for the first time in more than a decade (1998).

Data analysis in chapter 3 was limited due to inconsistencies in the experimental design. Nevertheless, the information presented represents some of the only hybrid aspen biomass results available in North America. Establishing permanent fixed plots across all sites and measuring all plots on a uniform basis would allow for additional analysis in the future. There was no family information available on the hybrid aspen planting stock at the time of establishment in this study. In future trials, labeling unique families during the outplanting process would allow for clone-specific analysis and further selection opportunities.

A number of assumptions were made in chapter 4 to generate results useful for comparison to fossil fuel emissions associated with energy production. In the time since the original report was published (Domke et al. 2008a), advancements in inventory data have improved our ability to estimate biomass and carbon stocks by unique tree and stand attribute (i.e., tops and limbs, bolewood, stumps, saplings, belowground). This update eliminates biomass attribute assumptions and provides several additional sources of biomass and carbon to consider in analyses. While this is a major improvement in the inventory system, a general lack of consistency remains within carbon accounting studies. For example, in our analysis in chapter 4, we compared CO_2 emissions over a 100-year time horizon. While this time period may make sense from a forest management perspective, it may not be the most appropriate time period to account for carbon flows in forests from a policy or atmospheric science perspective. Until a universally agreed upon time horizon is established for carbon estimation in forests, it may be useful to provide carbon flow estimates over multiple temporal scales, ranging from much shorter, to potentially longer than the 100-year time horizon used in our study. This approach would provide a more complete picture of the potential carbon benefits or consequences of woody biomass utilization for energy in the near and long term.

Bibliography

Adamsen, A.P.S., and G.M. King. 1993. Methane consumption in temperate and subarctic forest soils: rates, vertical zonation, and responses to water and nitrogen. *Applied and Environmental Microbiology* 59(2):485-490.

Alban, D.H. 1982. Effects of nutrient accumulation by aspen, spruce, and pine on soil properties. *Soil Science Society of America Journal* 46, 853-861.

Alban, D.H. and D.A. Perala. 1990. Impact of aspen timber harvesting on soils. In *Sustained Productivity of Forest Soils*. ed. S.P. Gessel, D.S. Lacate, G.F. Weetman, R.F. Powers, 377-391. Faculty of Forestry, University of British Columbia, Vancouver, BC.

Alban, D.H., and J. Pastor. 1993. Decomposition of aspen, spruce, and pine boles on two sites in Minnesota. *Canadian Journal of Forest Research* 23:1744-1749.

Alban, D.H., Perala, D.A., Jurgensen, M.F., Ostry, M.E. and J.R. Probst. 1991. Aspen Ecosystem Properties in the Upper Great Lakes. USDA Forest Service Research Paper 300. USDA Forest Service North Central Research Station, St Paul, MN.

Almendinger, J.C. 1997. Minnesota Bearing Tree Data Base. Minnesota Department of Natural Resources Biological Report Number 56.

Andrejak, G.E. and B.V. Barnes. 1969. A seedlings population of aspens in southeastern Michigan. *Michigan Journal of Botany* 8:189-202.

Arikian, M.J., Peuttmann, K.J., Davis, A.L., Host, G.E. and J.C. Zasada. 1998. Harvesting effects on soil properties and tree regeneration in pure and mixed aspen stands. In *Proceedings, Improving forest productivity for timber…a key to sustainability, December 1-3, 1998, Duluth, MN*, ed. A.R. Ek and B. ZumBahlen, 329-331. Department of Forest Resources, University of Minnesota, St. Paul, MN.

Arthur, M.A., Trittonne, L.M., and T.J. Fahey. 1993. Dead bole mass and nutrients remaining 23 years after clear-felling of a northern hardwood forest. *Canadian Journal of Forest Research* 23:1298-1305.

Balatinecz, J.J. and D.E. Kretschmann. 2001. Properties and utilization of poplar wood. In *Poplar Culture in North America*, ed. D.I. Dickmann, J.G. Isebrands, J.E. Eckenwalder, and J. Richardson, 277-291. NRC Research Press, National Research Council of Canada, Ottawa, ON, Canada.

Banfield, A.W.F. 1974. The mammals of Canada. University of Toronto Press, Toronto, Ontario.

Barnes, B.V. 1961. Hybrid aspens in the lower peninsula of Michigan. *Rhodora* 63:311-324.

Barnes B.V. 1966. The clonal growth habit of American aspens. *Ecology* 47: 439-447.

Bates, P.C., Blinn, C.R. and A.A. Alm. 1993. Harvesting impacts on quaking aspen regeneration in northern Minnesota. *Canadian Journal of Forest Research* 23: 2403-2412.

Bates, P.C., Sucoff, E. and C.R. Blinn. 1998. Short term flooding effects on root suckers of quaking aspen. *Northern Journal of Applied Forestry* 15:169-173.

Becker, D.R., Moseley, C., and C. Lee. 2010a. A supply chain analysis framework for assessing state-level forest biomass utilization policies in the United States. *Biomass and Bioenergy*. In press.

Becker, D.R., Klapperich, J.J., Domke, G.M., Kilgore, M.A., D'Amato, A.W., Current, D.A. and A.R. Ek. 2010b. Outlook for forest biomass availability in Minnesota: physical, environmental, economic, and social availability. UMN Department of Forest Resources Staff Report 210.

Bell, F.W., Pitt, D.G., Morneault, A.E., and S.M. Pickering. 1999. Response of immature trembling aspen to season and height of cut. *Northern Journal of Applied Forestry* 16:108-114.

Bella, I.E. and R.C. Yang. 1990. Should we thin young aspen stands. In *Aspen management for the 21st century: proceedings of a symposium held November 20-21, 1990, in Edmonton, Alberta in conjunction with the 12th annual meeting of the Poplar Council of Canada*, ed. S. Navratil and P.B. Chapman, 135-142.

Belleau, A., Brais, S., and D. Pare. 2006. Soil nutrient dynamics after harvesting and slash treatments in boreal aspen stands. *Soil Science Society of America Journal* 70: 1189-1199.

Benson, M.K. and D.W. Einspahr. 1967. Early growth of diploid, triploid and triploid hybrid aspen. *Forest Science* 13:150-155.

Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystems. In Forests and Global Change: vol. I. Opportunities for Increasing Forest Cover, eds., Sampson, R.N., and D. Hair, American Forestry Association. 285 p.

Borges J.G. and H.M. Hoganson. 1999. Assessing the impact of management unit design and adjacency constraints on forest wide spatial conditions and timber revenues. *Canadian Journal of Forest Research* 29: 1764-1774.

Bormann, F.H., Likens, G.E., Fisher, D.W. and R.S. Pierce. 1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. *Science* 159: 882-884.

Brinkman, K.A. and E.L. Roe. 1975. Quaking aspen: silvics and management in the Lake States. USDA Forest Service Agriculture Handbook 486. USDA Forest Service, Washington, DC.

Brinker, R.W., Kinard, J., Rummer, B., and B. Lanford. 2002. Machine rates for selected forest harvesting machines. Circular 296. Auburn, AL: Alabama Agricultural Experiment Station.

Brown, J.K. and N.V. DeByle. 1987. Fire damage, mortality, and suckering in aspen. *Canadian Journal of Forest Research* 17:1100–1109.

Brown, S., Schroeder, P., and R. Birdsey. 1997. Aboveground biomass distribution of U.S. eastern hardwood forests and the use of large trees as an indicator of past forest development. *Forest Ecology and Management* 96: 37-47.

Buongiorno, J., and J.K. Gilless. 2003. *Decision Methods for Forest Resource Management.* Boston, MA: Academic Press.

Burns, R.M. and B.H. Honkala. 1990. *Silvics of North America: 1. Conifers; 2.* Hardwoods. Agriculture Handbook 654. Washington DC: USDA Forest Service.

Byelich, J.D., Cook, J.L. and R.I. Blouch. 1972 Management for deer. In *Aspen: symposium proceedings*, 120-125. USDA Forest Service General Technical Report NC-1. USDA Forest Service, North Central Experiment Station, St. Paul, MN.

Carbon On Line Estimator 2005. USDA Forest Service and National Council on Air and Stream Improvement. Available online at: http://ncasi.uml.edu/COLE/. Last accessed Feb 17, 2010.

Carey, A.B., and M.L. Johnson. 1995. Small mammals in managed, naturally young, and old-growth forests. *Ecological Applications* 5: 336–352.

Chueng, N., and S. Brown. 1995. Decomposition of silver maple (*Acer saccharinum* L.) woody debris in a central Illinois bottomland forest. *Wetlands* 15:232-241.

Cleland, D.T., Leefers, L.A. and D.I. Dickmann. 2003. Ecology and Management of Aspen: A Lake States Perspective. In *Sustaining aspen in western landscapes: symposium proceedings; 13-15 June 2000; Grand Junction, CO,* ed. W.D. Shepperd, D. Binkley, D.L. Bartos, T.J. Stohlgren and L.G. Eskew, 81-100. USDA Forest Service General Technical Report RMRS-P-18. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Climate Registry. 2005. http://www.ghgprotocol.org/calculation-tools/all-tools

Comeau, P.G. 2002. Relationships between stand parameters and understory light in boreal aspen stands. *B.C. Journal of Ecosystem Management* 1:103-110.

Comer, P.J. Albert, D.A., Wells, H.A., Hart, B.L., Raab, J.B., Price, D.L., Kashian, D.M., Corner, R.A. and D.W. Schuen. 1995. Michigan's native landscape, as interpreted from the General Land Office Surveys 1816-1856. Michigan Natural Features Inventory, Lansing, MI.

Cost, N.D., Howard, J., Mead, B., McWilliams, W.H., Smith, W.B., Van Hooser, D.D., and E.H. Wharton. 1990. The Biomass Resource of the United States, USDA Forest Service, General Technical report WO-57, Washington, DC, p. 21.

David, A. J. 2003. Aspen/Larch Genetics Cooperative 2003 Annual Report. Report #14. Department of Forest Resources, University of Minnesota

David, A.J., Zasada, J.C., Gilmore, D.W. and S.M. Landhausser. 2001. Current trends in the management of aspen and mixed aspen forest for sustainable production. *The Forestry Chronicle* 77: 525-532.

DeByle, N.B. and R.P. Winokur. 1985. Aspen ecology and management in the western United States. USDA Forest Service General Technical Report RM-119. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Dickmann, D.I. 2006. Silviculture and biology of short-rotation woody crops in temperate regions: Then and now. *Biomass and Bioenergy* 30:696-705.

Domke, G.M., David, A.J., D’Amato, A.W., Ek, A.R., and Wykoff, G. In press. Hybrid aspen response to shearing in Minnesota: implications for biomass production. *Northern Journal of Applied Forestry*.

Domke, G.M., Ek, A.R., Becker, D.R., D’Amato A.W., and F. Fredrickson. In prep. 1. Model framework for the assessment of carbon flows associated with the procurement and utilization of forest harvest residues for energy. Intended journal: *Biomass and Bioenergy*.

Domke, G.M., Ek, A.R., and A.W. D'Amato. In prep. 2. Model development for the rapid estimation of forest-derived biomass availability. Intended journal: *Northern Journal of Applied Forestry*.

Domke, G.M. and Ek, A.R. Model development for rapid estimation of woody biomass availability. Society of American Foresters National Convention. September 30, 2009. Orlando, FL.

Domke, G.M., Ek, A.R., Becker, D.R., Espeleta, J.F., D'Amato, A.W., Reich, P.B., Suh, S., Kilgore, M.A., Current, D.A., Hoganson, H.M., Burk, T.E., and Blinn, C.R. 2008a. Assessment of Carbon Flows Associated with Forest Management and Biomass Procurement for the Laskin Biomass Facility. UMN Department of Forest Resources Staff Report 198.

Domke, G.M., Ek, A.R., Kilgore, M.A., and David, A.J. 2008b. Aspen in the Lake States: A Research Assessment. National Council for Air and Stream Improvement, Inc. (NCASI) Technical Bulletin No. 0955.

Domke, G., Ek, A., Kilgore, M., Palik, B., Katovich, S. and S. Finley. 2006. Web based forest management guides for the north central region. In *Proceedings of the Society of American Foresters, October 25-29, Pittsburgh, PA.* CD-ROM. Society of American Foresters, Bethesda, MD.

Eckenwalder, J.E. 1996. Systematics and evolution of Populus. P. 7-32 in Biology of Populus and its implications for management and conservation, Stettler, R.F., H.D. Bradshaw Jr., P.E. Heilman, and T.M. Hinckley (eds.). NRC Research Press, Ottawa, ON.

Einspahr, D.W. and L.L. Winton. 1977. Genetics of quaking aspen. USDA Forest Service Research Paper WO-25. USDA Forest Service, Washington, DC.

Einspahr, D.W. and G.W. Wykoff. 1990. North American Aspen: Timber Supply, Utilization, and Research. *Northern Journal of Applied Forestry* 7: 168-171.

Ek, A.R. 2007. Strategies for improving forest productivity in Minnesota. Interagency Information Cooperative (IIC). Available online at: http://iic.gis.umn.edu/documents/forestproductivity.pdf. Last accessed Feb 10, 2010.

Ek, A. 1985. A formula for the total cubic foot stem volume of small trees in the Lake States. *Northern Journal of Applied Forestry* 2:3-3.

Ek, A. R. and J.D. Brodie. 1975. A preliminary analysis of short-rotation aspen management. *Canadian Journal of Forest Research* 5: 245-258.

Elkinton, J.S., Healy, W.M., Buonaccorsi, J.F., Boettner, G.H., Hazzard, A.M., Smith, H.R. and A.M. Liebhold. 1996. Interactions among gypsy moths, white-footed mice, and acorns. *Ecology* 77: 2332-2342.

Energy Information Administration. 2009. Electric Power Annual 2007. Available online at: http://tonto.eia.doe.gov/FTPROOT/electricity/034807.pdf. Last accessed Feb 17, 2010.

Energy Information Administration. 2008. Minnesota Renewable Electricity Profile. Available online at: http://www.eia.doe.gov/cneaf/solar.renewables/page/state_profiles/minnesota.html. Last accessed Aug 25, 2010.

Environmental Protection Agency. 2002. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000. US Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-02-003.

Environmental Protection Agency. 1995. AP 42, Fifth Edition: Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources. US Environmental Protection Agency, Office of Atmospheric Programs.

Every, A.D. and D. Wiens. 1971. Triploidy in Utah aspen. *Madrono* 21:138-147.

Farmer Jr., R.E. 1962. Aspen root sucker formation and apical dominance. *Forest Science* 8: 403-410.

Finley, R.W. 1976. Original vegetation cover of Wisconsin, compiled from U.S. General Land Office notes. Madison, WI: University of Wisconsin Extension.

Frey, B.R., Lieffers, V.J., Landhausser, S.M., Comeau, P.G. and K.J. Greenway. 2003. An analysis of sucker regeneration of trembling aspen. *Canadian Journal of Forest Research* 33: 1169-1179.

Frey, B.F., Leiffers, V.J., Hogg, E.H. and S.M. Landhausser. 2004. Predicting landscape patterns of aspen dieback: mechanisms and knowledge gaps. *Canadian Journal of Forest Research* 34: 1379-1390.

Friedman S.K. and P.B. Reich. 2005. Regional legacies of logging: Departure from presettlement forest conditions in northern Minnesota. *Ecological Applications* 15: 726-744.

Freppaz, D. Minciardi, R., Robba, M., Rovatti, M., Sacile, R. and A. Taramasso. 2004. Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass and Bioenergy* 26: 15-25.

Froehlich, H.A. 1977. The physical effects of timber harvesting on forest soils. In *Proceedings of the Society of American Foresters, October 2-6, Albuquerque, NM*, 229-237. Society of American Foresters, Bethesda, MD.

Frombo, F. Minciardi, R., Robba, M., Rosso, F., and R. Sacile. 2009. Planning woody biomass logistics for energy production: A strategic decision model. *Biomass and Bioenergy* 33: 372-383.

Gevorkiantz, S.R. and L.P. Olsen. 1955. Composite volume tables for timber and their application in the Lake States. USDA For. Serv. Tech. Bull. 1104. 51 p.

Gómez, D.R., Watterson, J.D., Branca, B.A., Chia, H., Marland, G., and E. Matsika. 2006 Stationary Combustion. IPCC Guidelines for National Greenhouse Gas Inventories.

Graham, G.M. and D.R. Betters. 1985. A simulation model for economic analysis of timber/forage production alternatives in Rocky Mountain aspen stands. *Forest Ecology and Management* 10: 313-321.

Graham, S.A. Harrison Jr., R.P. and C.E. Westell Jr. 1963. *Aspens: Phoenix trees of the Great Lakes Region*. The University of Michigan Press, Ann Arbor, MI.

Greacen, E.L. and R. Sands. 1980. Compaction of Forest Soils. A Review. *Australian Journal of Soil Resources* 18: 163-189.

Gingras, J.-F., and J. Favreau. 1996. Comparative cost analysis of integrated harvesting of roundwood and forest biomass. Special Report, SR-111. Quebec, Canada: Forest Engineering Research Institute of Canada.

Grier, C.C., Lee, K.M., Nadkarni, N.M., Klock, G.O. and P.J. Edgerton. 1989. Productivity of forest of the United States and its relation to soil and site factors and management practices: a review. USDA Forest Service General Technical Report PNW-GTR-222. USDA Forest Service, Pacific Northwest Research Station, Portland, OR.

Grigal, D.F. 2000. Effects of extensive forest management on soil productivity. *Forest Ecology and Management* 138: 167-185.

Gullion, G.W. 1977. Maintenance of the aspen ecosystem as a primary wildlife habitat. In *Proceedings of the 13th International Congress on Game Biology, March 11-15, Atlanta GA*, ed. T.J. Peterle. Wildlife Society, Washington DC.

Gullion, G.W. 1984. Managing northern forest for wildlife. Minnesota Agricultural Experimental Station. Miscellaneous Journal Series Publication 13. University of Minnesota, St. Paul, MN.

Gullion, G.W. 1987. Aspen management for ruffed grouse. In *Proceedings of the Society of American Foresters, Oct 18-21, 1987, Minneapolis, Minnesota.* Society of American Foresters, Bethesda, MD.

Gullion, G.W. 1990. Management of aspen for grouse and other wildlife – an update. In *Aspen symposium '89, Proceedings Symposium, July 25-27, 1989, Duluth, Minnesota*, ed. R.D. Adams. USDA Forest Service General Technical Report NC-140. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Guo, Z., Sun, C., and D.L. Grebner. 2007. Utilization of forest derived biomass for energy production in the U.S.A.: status, challenges, and public policies. *International Forestry Review* 2007 9: 748-758.

Haines, D.A. and R.W. Sando. 1969. Climatic conditions preceding historically great fires in the North Central Region. USDA Forest Service Research Paper NC-34. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Hall, R.B., Hilton, G.D., and C.A. Maynard. 1982. Construction lumber from hybrid aspen plantations in the Central States. *Journal of Forestry* 80:291-294.

Hamilton Jr. W.J. 1941. The Food of Small Forest Mammals in Eastern United States. *Journal of Mammalogy* 22: 250-263.

Hansen, M.H. and G.J. Brand. 2006. Michigan's Forest Resources in 2004. USDA Forest Service Resource Bulletin NC-255. USDA Forest Service, North Central Research Station, St. Paul, MN.

Harmon, M.E., Krankine, O.N., and J. Sexton. 2000. Decomposition vectors: a new approach to estimating woody detritus decomposition dynamics. *Canadian Journal of Forest Research* 30:76-84.

Heeney, C.J., Kemperman, J.A. and G. Brown. 1980. A silvicultural guide to the aspen working group in Ontario. OMNR Division of Forestry, Forest Research Branch, Toronto, ON.

Hoffmann-Schielle, C., Jug, A., Makeschin, C., and K.E. Rehfuess. 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.

Hoganson, H.M. and D.W. Rose. 1984. A simulation approach for optimal timber management scheduling. *Forest Science* 30: 220-238.

Holcomb, C.J. and R.D. Jones. 1938. The Antrim area: a study of farm woodland conditions on a cut-over area of lower Michigan. USDA Forest Service, Lake States Forest Experiment Station, University Farm, St. Paul, MN.

Hoover, R.L. and D.L. Wills. 1987. Managing forested lands for wildlife. Colorado Division of Wildlife and USDA Forest Service, Rocky Mountain Region. Denver, CO.

Hove, G.P. 1990. A biological and financial stand development analysis of aspen, red pine, and jack pine management in Beltrami Country, Minnesota. University of Minnesota, College of Natural Resources, M.S. Thesis. 79 pp.

Husain, S.A. 1996. Forest protection expenditures in Minnesota's Aspen Birch unit. M.Sc. thesis. University of Minnesota, Department of Applied Economics.

Institute of Paper Chemistry 1988. Production and intensive management of genetically improved aspen. Project 3537. Report Three. February 25, 1988. The Institute of Paper Chemistry, Appleton, WI.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jenkins, J.C., Chjnacky, D.C., Heath, L.S., and R.A. Birdsey. 2003. National-scale biomass estimators for United States tree species. *Forest Science* 49:12-35.

Johnsson, H. 1940. Cytological studies of diploid and triploid Populus tremula and of crosses between them. *Hereditas Lund* 26: 321-352.

Johnsson, H. 1953. ungdomsutveckling och ett försök till farmtidsprognos. Svenska Skogsvårdsföreningens tidsskrift 51: 73-96 (In Swedish).

Jones, B.S., Berguson, W.E. and J.J. Vogel. 1990. Aspen thinning as a viable cultural tool. In *Aspen Symposium '89 Proceedings, July 25-27, Duluth, MN*, ed. R.D. Adams, 205-210.USDA Forest Service General Technical Report NC-140. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Karacic, A., Verwijst, T., and M. Weih. 2003. Above-ground woody biomass production of short-rotation Populus plantations on agricultural land in Sweden. *Scandinavian Journal of Forest Research* 18:427-437.

Kauter, D., Lewandowski, I., and W. Claupeina. 2003. Quantity and quality of harvestable biomass from Populus short rotation coppice for solid fuel use -- review of the physiological basis and management influences. *Biomass and Bioenergy* 24:411–427.

Kemperman, J.A. 1977. Aspen clones: development, variability and identification. OMNR Division of Forestry Ontario Forest Research Note 12. OMNR Division of Forestry, Forest Research Branch, Maple, ON.

Kemperman, J.A. and B.V. Barnes. 1976. Clone size in American aspens. *Canadian Journal of Botany* 54:2603-2607.

Kilgore, M.A. and D.G. MacKay. 2007. Trends in Minnesota's forest land real estate market: potential implications for forestland uses. *Northern Journal of Applied Forestry* 24: 37-42.

Kittredge, J. 1938. The interrelations of habitat, growth rate, and associated vegetation in the aspen community of Minnesota and Wisconsin. *Ecological Monographs* 8: 151-246.

Kittredge, J. and S.R. Gevorkiantz. 1929. Forest possibilities of aspen lands in the lake states. Minnesota Agricultural Experiment Station Technical Bulletin 60.

King, J.S., Pregitzer, K.S., and D.R. Zak. 1999. Clonal variation in above- and below-ground growth responses of Populus tremuloides Michaux: Influence of soil warming and nutrient availability. *Plant and Soil* 217:119-130.

King, J.S., C.P. Giardina, K.S. Pregitzer, and A.L. Friend. 2007. Biomass partitioning in red pine (Pinus resinosa) along a chronosequence in the Upper Peninsula of Michigan. *Canadian Journal of Forest Research* 37:93-102.

Krzic, M., Page, H., Newman, R.F. and K. Broersma. 2004. Aspen regeneration, forage production, and soil compaction on harvested and grazed boreal aspen stands. *BC Journal of Ecosystems and Management* 5: 30–38.

Kubiske, M.E., Quinn, V.S., Marquardt, P.E. and D.F. Karnosky. 2007. Effects of elevated atmospheric CO2 and/or O3 on intra- and interspecific competitive ability of aspen. *Plant Biology* 9: 342-355.

Lamb, F.M. 1967. Aspen wood characteristics, properties and uses: A review of literature. USDA Forest Service Research Paper NC-13. USDA Forest Service, North Central Experiment Station, St. Paul, MN.

Lambert, R.L. Lang, G.E. and Reiners, W.A. 1980. Loss of mass and chemical change in decaying boles of a subalpine balsam fir forest. *Ecology* 61:1460-1473.

Li, B., and R. Wu. 1997. Heterosis and genotype x environment interaction of juvenile aspen in two contrasting sites. *Canadian Journal of Forest Research* 27:1525-1537.

Liesebach, M., von Wuehlisch, G. and H.-J. Muhs. 1999. Aspen for short-rotation coppice plantations on agricultural sites in Germany: effects of spacing and rotation time on growth and biomass production of aspen progenies. *Forest Ecology and Management* 121:25-39.

Lindroth, R.L. 2001. Adaptions of quaking aspen for defense against damage by herbivores and related environmental agents. In *Sustaining aspen in western landscapes: symposium proceedings; 13-15 June 2000; Grand Junction, CO,* ed. W.D. Shepperd, D. Binkley, D.L. Bartos, T.J. Stohlgren and L.G. Eskew, 81-100. USDA Forest Service General Technical Report RMRS-P-18. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Lindsey, J. P. and R.L. Gilbertson. 1978. Basidiomycetes that decay aspen in North America. J. Cramer, Lehre, West Germany.

Little Jr., E. L. 1971. Atlas of United States trees: Vol. 1. Conifers and important hardwoods. USDA Forest Service Miscellaneous Publication 1146. USDA Forest Service, Washington, DC.

Little Jr., E.L., Brinkman, K.A. and A.L. McComb. 1957. Two natural Iowa hybrid poplars. *Forest Science* 3: 253-262.

Luoranen, J., Lappi, J., Zhang, G., and H. Smolander. 2006. Field performance of hybrid aspen clones planted in summer. *Silva Fennica* 40:257-269.

MacMillian, P.C. 1988. Decomposition of coarse woody debris in an old-growth Indiana forest. *Canadian Journal of Forest Research* 18:1353-1362.

Madritch M.D. and M.D. Hunter. 2002. Phenotypic diversity influences ecosystem functioning in an oak sandhills community. *Ecology* 83: 2084-90.

Madritch, M., Donaldson, J.R., and R.I. Lindroth. 2006. Genetic identity of *Populus trembuloides* litter influences decomposition and nutrient release in a mixed forest stand. *Ecosystems* 9: 528-537.

Maini, J.S. 1967. Variation in the vegetation propagation of *Populus* in natural populations. *Bulletin of the Ecological Society of America* 48: 75-76.

Maini, J.S. 1968. Silvics and ecology of *Populus* in Canada. In *Growth and utilization of poplar in Canada*, ed. J.S. Maini and J.H. Cayford, 20-69. CDFRD Forestry Branch Department Publication 1205. CDFRD, Forestry Branch, Ottawa, ON.

Maini, J.S. and K.W. Horton. 1964. Influence of temperature and moisture on initiation and initial development of *Populus trembuloides* suckers. CDFRD Forest Research Branch Report 64-0-11. CDFRD, Forest Research Branch, Ottawa, ON.

Manion, P. D. 1991. *Tree Disease Concepts*. 2nd ed. Prentice-Hall, Englewood Cliffs, NJ.

McCarl, B.A. and F.O. Boadu. 2009. Bioenergy and U.S. renewable fuels standards: law, economic, policy/climate change and implementation concerns. *Drake Journal of Agricultural Law* 14: 43-73.

Megonigal, J.P. and A.B. Guenther. 2008. Methane emissions from upland forest soils and vegetation. *Tree Physiology* 28: 491-498.

Merrill, S.B., Cuthbert, F.J. and G. Oehlert. 1998. Residual patches and their contribution to forest-bird diversity on northern Minnesota aspen clearcuts. *Conservation Biology* 12: 190-199.

Miles, P.D. 2008. Forest inventory mapmaker web-application version 3.0. St. Paul, MN: USDA Forest Service, North Central Research Station.

Minnesota Department of Natural Resources (MNDNR). 2010a. DRAFT Economic opportunities for Minnesota wood. St. Paul, MN: Department of Natural Resources, Division of Forestry.

Minnesota Department of Natural Resources (MNDNR). 2010b. Active Woody Biomass Energy Facilities in Minnesota. St. Paul, MN: Department of Natural Resources, Division of Forestry.

Minnesota Department of Natural Resources (MNDNR). 2009. Minnesota's Forest Resources. St. Paul, MN: Department of Natural Resources, Division of Forestry

Minnesota Department of Natural Resources (MNDNR). 2007. Minnesota's Forest Resources. St. Paul, MN: Department of Natural Resources, Division of Forestry

Minnesota Department of Natural Resources (MNDNR). 2006a. Public stumpage price review 2006: Volume of timber sold and average price received by public agencies in Minnesota. St. Paul, MN: Department of Natural Resources, Division of Forestry

Minnesota Department of Natural Resources (MNDNR). 2006b. Minnesota Logged Area Residue Analysis. St. Paul, MN: Department of Natural Resources, Division of Forestry

Minnesota Department of Natural Resources (MNDNR). 2004. Minnesota's Forest Resources. St. Paul, MN: Department of Natural Resources, Division of Forestry.

Minnesota Department of Natural Resources (MNDNR). 1997. Forest Development Manual. St. Paul, MN: Department of Natural Resources, Division of Forestry

Minnesota Department of Natural Resources (MNDNR). 1981. Timber Scaling Manual. St. Paul, MN: Department of Natural Resources, Division of Forestry

Minnesota Forest Resources Council. 2007. Forest Biomass Harvesting in Sustaining Minnesota Forest Resources: Voluntary Site-Level Forest Management Guidelines for Landowners, Loggers and Resource Managers. 41 p.

Minnesota Statute 216C.0. 2007. Next Generation Energy Act of 2007. Available online at: https://www.revisor.mn.gov/data/revisor/slaws/2007/0/136.pdf. Last accessed Feb 10, 2010.

Mitchell, C.P. 2000. Development of decision support systems for bioenergy applications. *Biomass and Bioenergy* 18: 265-278.

Mitton, J.B. and M.C. Grant. 1996. Genetic variation and the natural history of quaking aspen. *Bioscience* 46: 25-31.

Morris, D.M. 1997. The role of long-term site productivity in maintaining healthy ecosystems: A prerequisite of ecosystem management. *The Forestry Chronicle* 73: 731-740.

Moses, R.A. and S. Boutin. 2001. The influence of clear-cut logging and residual leave material on small mammal populations in aspen-dominated boreal mixedwoods. *Canadian Journal of Forest Research* 31: 483-495.

Mukhin, V.A. and P.Y. Voronin. 2009. Methanogenic activity of woody debris. *Russian Journal of Ecology*. 40: 149-153.

Mundell, T.L., S.M. Landhäusser, and V.J. Lieffers. 2008. Root carbohydrates and aspen regeneration in relation to season of harvest and machine traffic. *Forest Ecology and Management* 255:68-74.

National Oceanic and Atmospheric Administration. 2004. *Climatography of the United States No. 20 1971-2000 Station: Grand Rapids, MN*. Available online at www.ncdc.noaa.gov/oa/climate/normals/usnormals.html; last accessed June 3, 2009.

Natural Resources Conservation Service. 2009. *Web Soil Survey*. Soil Survey Staff, Natural Resources Conservation Service, USDA. Available online at http://websoilsurvey.nrcs.usda.gov/; last accessed May 14, 2009.

Ney, R.A., J.L. Schnoor, and M.A. Mancuso. 2002. A methodology to estimate carbon storage and flux in forestland using existing forest and soils databases. *Environmental Monitoring and Assessment* 78:291-307.

Nordeen, P.A. 1968. Economic evaluation of precommercial thinning in good-site aspen. University of Minnesota, School of Forestry, M.S. thesis. 19 pp.

Ostry, M.E., Anderson, N.A. Rugg, D.J. and J.T. Ward. 2004. Long-term response of precommercially thinned aspen clones to Hypoxylon canker. USDA Forest Service Research Paper NC-341. USDA Forest Service, North Central Research Station, St. Paul, MN.

Ostry, M.E. and N.A. Anderson. 2009. Genetics and ecology of the *Entoleuca mammata-Populus* pathosystem: Implications for aspen improvement and management. *Forest Ecology and Management* 257: 390-400.

Ostry, M.E., Wilson L.F., McNabb, H.S. and L.M. Moore. 1989. A guide to insect, disease, and animal pests of poplars. USDA Forest Service Agricultural Handbook 677. USDA Forest Service, Washington DC.

Peet, R.K. and N.L. Christensen. 1987. Competition and tree death. *Bioscience* 37:586–595.

Pennock D.J. and C. van Kessel. 1995. Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. *Geoderma* 75: 13-32.

Perala, D.A. 1977. Manager’s handbook for aspen in the North Central States. USDA Forest Service General Technical Report NC-324. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Perala, D.A. 1978. Thinning strategies for aspen: a prediction model. USDA Forest Service Research Paper NC-161. USDA Forest Service, North Central Research Experiment Station, St. Paul, MN.

Perala D.A., 1983. Shearing restores full productivity to sparse aspen stands. USDA Forest Service Research Note NC-296. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Perala, D.A., 1990. *Populus trembuloides* Michx. Quaking aspen. In *Silvics of North America. Volume 2, Hardwoods*, ed. R.M. Burns and B.H. Honkala. USDA Forest Service Agricultural Handbook 654. USDA Forest Service, Washington DC.

Perala, D.A., Russell, J. 1983. Aspen. In *Silvicultural systems of the major forest types of the United States*, ed. R.M. Burns, 113-115. USDA Forest Service Agricultural Handbook 445. USDA Forest Service, Washington, DC.

Peterson, E.B. and N.M. Peterson. 1992. Ecology, management, and use of aspen and balsam poplar in the prairie provinces, Canada. Forestry Canada, Northwest Region, Northern Forestry Center, Edmonton, Alberta. Spec. Rep. 1.

Petit, D.R. 1985. Habitat and snag selection by woodpeckers in a clearcut: an analysis using artificial snags. *Wilson Bulletin* 97: 525-533.

Peto, F.H. 1938. Cytology of poplar species and natural hybrids. *Canadian Journal of Research* 16:445-455.

Piva, R.J. 2006. Pulpwood production in the North-Central Region, 2004. USDA Forest Service Bulletin NC-265. USDA Forest Service, North Central Research Station, St. Paul.

Potter-Witter, K. and C.W. Ramm. 1992. Aspen Supply, Use, and Demand in Michigan. *Northern Journal of Applied Forestry* 9: 10-14.

Powers, R.F., Scott, D.A., Sanchez, F.G., Voldseth, R.A., Page-Dumroese, D., Elioff, J.D. and D.M. Stone. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management* 220: 31-50.

Public Law H.R. 776. 1992. Energy Policy Act of 1992. January 3, 1992. Available online at: http://thomas.loc.gov/cgi-bin/query/z?c102:H.R.776.ENR Last accessed Feb. 10, 2010.

Public Law 109–58. 2005. Energy Policy Act of 2005. August 8, 2005. Available online at http://www.epa.gov/swerust1/fedlaws/publ_109-058.pdf. Last accessed Feb. 10, 2010.

Public Law 110–140. 2007. Energy Independence and Security Act of 2007. Available online at http://frwebgate.access.gpo.gov/cgi bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf. Last accessed Feb. 10, 2010.

Puettmann, K. J. and A.R. Ek. 1999. Status and trends of silvicultural practices in Minnesota. *Northern Journal of Applied Forestry* 16: 203-210.

R version 2.10.0. 2009. Copyright (C) 2009 The R Foundation for Statistical Computing. ISBN 3-900051-07-0.

Roberds, J.H., and J.W. Bishir. 1997. Risk analyses in clonal forestry. *Canadian Journal of Forest Research* 27:425-432.

Rogers, L.L., Wilker, G.A. and A.W. Allen. 1988. Managing northern forests for black bears. In *Proceedings of the Society of American Foresters National Convention. October 18-21, 1987. Minneapolis Minnesota.* Society of American Foresters. Bethesda, MD.

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

Rytter, L., and L.-G. Stener. 2003. Productivity and thinning effect in hybrid aspen (Populus tremula L. P. tremuloides Michx.) stands in southern Sweden. *International Journal of Forest Research* 78:285-295.

Shier, G.A. 1981. Physiological research on adventitious shoot development in aspen roots. USDA For. Serv. Gen. Tech. Rep. INT-107. 12 p.

Schier, G.A. and J.C. Zasada. 1973. Role of carbohydrate reserves in the development of root suckers in *Populus trembuloides*. *Canadian Journal of Forest Research* 3: 243-250.

Schopmeyer, C.S. 1974. Seeds of woody plant in the United States. USDA Forest Service Agricultural Handbook 450. USDA Forest Service, Washington, DC.

Schulte, L.A. and G.J. Niemi. 1998. Bird communities of early-successional burned and logged forest. *The Journal of Wildlife Management* 62: 1418-1429.

Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., Elobeid, A., Faiosa, J., Tokgoz, S., Hayes, D., and T.-H. Yu. 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319:1238-1240.

Schnell, S., and G.M. King. 1994. Mechanistic analysis of ammonium inhibition of atmospheric methane consumption in forest soils. *Applied and Environmental Microbiology* 60(10): 3514-3521.

Shands, W. E. and R.G. Healy. 1977. The lands nobody wanted. The Conservation Foundation, Washington, DC.

Sheppard, W.D., 2001. Manipulations to Regenerate Aspen Ecosystems. USDA Forest Service RMRS-P-18. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Sitaula, B.K., Bakken, L.R., and G. Abrahamsen. 1995. CH4 uptake by temperate forest soils: effect of N input and soil acidification. *Soil Biology and Biochemistry* 27(7):871-880.

Skinner, Q.D., Speck, Jr., J.E., Smith, M. and J.C. Adams. 1984. Stream water quality as influenced by beaver within grazing systems in Wyoming. *Journal Range Management* 37: 142-146.

Sorenson, R.W. 1968. Size of aspen crop tress little affected by initial sucker density. USDA Forest Service Research Note NC-51. USDA Forest Service, North Central Experiment Station, St Paul, MN.

Spencer Jr., J.S. and H.W. Thorne. 1972. Wisconsin's 1968 timber resource. USDA Forest Service Resource Bulletin NC-15. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Stanosz, G.R. and R.F. Patton. 1987a. Armillaria root rot in aspen stands after repeated short rotations. *Canadian Journal of Forest Research* 17: 1001-1005.

Stanosz, G.R. and R.F. Patton. 1987b. Armillaria root rot in Wisconsin aspen sucker stands. *Canadian Journal of Forest Research* 17: 995-1000.

Steneker, G.A. 1972. Size and suckering of trembling aspen (*Populus tremuloides*) clones in Manitoba. Ph.D. thesis, University of Michigan.

Steneker, G.A., 1974. Factors affecting the suckering of trembling aspen. *The Forestry Chronicle* 50: 32-34.

Stokes, B.J., and W.F. Watson. 1991. Wood recovery with in-woods flailing and chipping. *Tappi Journal* 74(9):109–113.

Stone, E.L., Swank, W.T. and J.W. Hornbeck. 1979. Impacts of timber harvest and regeneration systems on streamflow and soils in the eastern deciduous region. In: *Forest Soils and Land Use,* ed. C.T. Youngberg, 516-535. Colorado State University, Fort Collins, CO.

Stone, D.M. 2001. Sustaining Aspen productivity in the Lake States. USDA Forest Service RMRS-P-18. USDA Forest Service, North Central Research Station, St. Paul, MN.

Sturos, J.A., Barron, R.M., Miyata, E.S., and H.M. Steinhilb. 1983. The economics of a mechanized multiproduct harvesting system for stand conversion of northern hardwoods. Res. Pap. NC-237. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station.

Telfer, E.S. 1993. Wildfire and the historical habitats of boreal forest avifauna. In *Proceedings from birds in the boreal forest workshop*, ed. D.G. Kunke. Northern Forestry Centre, Prince Albert, SK.

Thomas, J.W. 1979. Wildlife habitats in managed forest: the Blue Mountains of Oregon and Washington. USDA Agricultural Handbook 553. USDA, Washington, DC.

Tullus, A., Tullus, H., Vares, A., and A. Kanal. 2007. Early growth of hybrid aspen (Populus x wettsteinii Hamet-Ahti) plantations on former agricultural lands in Estonia. *Forest Ecology and Management* 245: 118-129.

Turner, C., Becker, D.R., Taff, S.J., Domke, G.M. and V. Gauto. Assessing forestation opportunities for carbon sequestration in Minnesota. *The Forestry Source* (15) 6: 12 and 15.

United States Census Bureau. 2008. U.S. Gazetteer. Available online at: http://www.census.gov/cgi-bin/gazetteer. Last accessed Jan. 17, 2009.

USDA Forest Service. 2010. FIA Data Mart Version 4.0. Available online at: http://199.128.173.17/fiadb4-downloads/datamart.html. Last accessed Aug 25, 2010.

USDA Forest Service. 2010. EVALIDator Version 4.01. Available online at: http://fiatools.fs.fed.us/Evalidator401/tmattribute.jsp Last accessed Aug, 25, 2010.

van Buijtenen, J.P., Joranson, P.N. and D.W. Einspahr. 1957. Naturally occurring triploid quaking aspen in the United States. In *Proceedings from the Society of American Foresters, 1957*, 62-64. Society of American Foresters, Bethesda, MD.

Walters, D.K. and A.R. Ek. 1993. Whole stand yield and density equations for fourteen forest types in Minnesota. *Northern Journal of Applied Forestry* 10: 75-86.

Wei, Y. and H.M. Hoganson. 2005. Landscape impacts from valuing core area in national forest planning. *Forest Ecology and Management* 218: 89-106.

Weih, M. 2004. Intensive short rotation forestry in boreal climates: present and future perspectives. *Canadian Journal of Forest Research* 34:1369-1378.

Weingartner, D.H. and R. Doucet. 1990. The quest for aspen management in eastern Canada. In *Aspen Symposium '89 Proceedings, July 25-27, Duluth, MN*, ed. R.D. Adams, 61-71. USDA Forest Service General Technical Report NC-140. USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

Westworth, D.A., Brusnyk, L.M. and G.R. Burns. 1984. Impact on wildlife of short-rotation management of boreal aspen stands. Canadian Forest Service Enforcement Project No. 203.

Yahner, R.H. 1991. Avian nesting ecology in small even-aged aspen stands. The Journal of Wildlife Management 55: 155-159.

Yu, Q. 2001. Can physiological and anatomical characters be used for selecting high yielding hybrid aspen clones. Silva Fennica 35:137-146.

Yu, Q., Tigerstedt, P.M.A., and M. Haapanen. 2001. Growth and phenology of hybrid aspen clones (Populus tremula L. x Populus tremuloides Michx.) Silva Fennica 35:15-25.

Zasada, Z.A. 1952. Does it pay to thin young aspen? Journal of Forestry 50:747–748.

Zasada, J.C., David, A.J., Gilmore, D.W., Landhausser, S.M., 2000. Ecology and silviculture of natural stands of Populus species. In *Poplar Culture in North America,* ed. D.I. Dickmann, J.G. Isebrands, J.E. Eckenwalder, and J. Richardson. NRC Research Press, National Research Council of Canada, Ottawa, ON.