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THE INFLUENCE OF STEM FORM AND VIGOR ON PRODUCT, GROWTH, AND SURVIVAL FOR NORTHERN COMMERCIAL HARDWOOD SPECIES

By

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B.S. James Madison University, 2012

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

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(in Forest Resources)

The Graduate School

The University of Maine

August 2017

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By Mark Castle

Thesis Advisor: Dr. Aaron R. Weiskittel

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
Degree of Master of Science
(in Forest Resources)
August 2017

Northern hardwood and mixed-wood forest types occupy a considerable percentage of the forest landscape across the Northeastern United States and portions of eastern Canada. While capable of producing valuable saw timber and veneer products**,** hardwood species demonstrate a wide range of stem quality resulting from the large variety of stem forms and defects that these species can manifest. The effect of different stem forms and damage has largely not been accounted for in predictions of volume, growth, and mortality. In addition to potential bias in growth and yield applications, the lack of quantification of these features has left the efficacy of silvicultural tools such as tree classification guides untested. Using a tree classification system developed by the Northern Hardwood Research Institute (NHRI), form and risk classifications were assigned to several commercial hardwood species across sites in Maine, New Hampshire, and New Brunswick. Regression analyses were used to accomplish the following objectives; 1) quantify sawlog recovery as a function of a trees size, form, and risk; 2) determine the occurrence of stem form and risk among species; 3) and evaluate the influence of stem form and risk on individual tree diameter growth and survival.

For the first chapter, a linear mixed effects model was used to quantify the proportion of sawlog material in individual trees. Results indicated three form classifications and a binary classification of risk were sufficient to account for variation in sawlog recovery. The average

proportion of sawlog was largest for trees with single straight stems and smallest for those displaying a large significant fork on the first 5 m of their stem. Stem damage also had substantial implications on product recovery where trees considered to be high-risk had overall lower proportions of sawlog volume. Using the simplified form and risk classes, a series of logistic regression models were developed to predict the occurrence of risk and form across hardwood species. Among the species in the analysis, yellow birch and red maple had the highest probability of being high-risk. Sugar maple had the highest probability of demonstrating good form while red maple and red oak were the most likely to have poor form.

In the second chapter continuous forest inventory data from five locations in Maine and New Hampshire were used to evaluate the influence of form and risk on tree growth and survival for hardwood species. The influence of form and risk on growth were analyzed by assessing bias in the regional diameter increment equation used in the Acadian Variant of the Forest Vegetation Simulator FVS-ACD and through development of a periodic annual increment model (PAI). The regional FVS-ACD equation tended to over predict for species and risk class while binary form and risk classifications were significant variables in the PAI model, although their effect was relatively small. A nonlinear model was used to quantify annualized individual tree survival. Trees with single straight stems had statistically higher survival probabilities compared to all other stem forms, however the magnitude of the difference in survival was not substantial.

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PROLOGUE

Northern hardwood and mixed-wood forest types account for a substantial amount of the forested land base of the Northeastern United States and portions of Canada adjacent to these regions. The tree species in these forest derive considerable economic value as they have the potential to yield valuable wood products (Nyland 1998; Cockwell and Casperen 2015). The importance of these species are reflected by recent trends in the forest product industry where in 2011, approximately 40% or 1.9 billion board feet of all harvested sawlog material harvested in Maine, New Hampshire, New York and Vermont was derived from hardwood species (NEFA 2013). The prevalence of the hardwood resource is expected to increase, particularly in some portions of the Northeast such as Maine as a result of previous management, the past spruce budworm outbreak, and the changing climate.

While capable of producing valuable wood products**,** hardwood species generally demonstrate a much greater range of product quality compared to softwood species (Cockwell and Casperen 2014). The variation in product quality results from the fact that hardwood species are prone to developing a large variety of stem damage and stem form characteristics such as sweep, significant forks and multiple stems (Fortin et al. 2009). The wide range of stem quality and vigor that hardwood species manifest can complicate the objectives of management for hardwood dominated or mixed-wood forests, where a common silvicultural treatment is selection cutting. From a management perspective the goal of this system is to simultaneously balance the objectives of short-term profit and retention of healthy stands for future harvests. Specifically, these objectives entail extracting merchantable volume and defective trees during each cutting cycle and leaving vigorous – low risk trees as future growing stock. However, given the large variety of stem quality and defects that hardwoods display, the task of prioritizing which trees to harvest or retain can become quite challenging. Ultimately, failure to balance the objectives of selection management can lead to severely degraded stands that only contain low vigor trees (Pothier et al. 2013).

To facilitate the process of prioritizing trees for harvest, tree classification systems have been developed which characterize defects that commonly arise on hardwood species. More specifically these systems have been used to either rate a tree's stem quality in terms of current value or assess a tree's future growth potential. While the presence of stem defects on hardwoods has long been observed, relatively little work has been done to quantify the influence of these attributes in relation to product value, volume, growth, and mortality. The exclusion of these attributes from formal quantitative analyses has not only left the efficacy of current classification systems untested, but may be leading to bias in predictions of growth and yield models which forest managers rely on to make accurate projections of timber resources. Recent work in Canada has demonstrated that tree classifications can be used to improve predictions in several applications. For instance, the ACBD system which is a stem quality classification system used in Quebec, has been shown to improve estimates of product recovery and value (Fortin et al. 2009; Cockwell and Casperen 2015). Similarly, tree vigor classifications have been recognized as significant variables in diameter increment and mortality models (Fortin et al. 2008; Hartmann et al. 2008).

Although recent findings have suggested that stem defects can have a significant role in reducing product potential and growth of hardwood species, several limitations still remain for hardwood research with respect to stem quality and vigor. First, most of the current work that has investigated the influence of stem defects has almost solely been conducted in Quebec across a relatively small number of hardwood species. As a consequence, it still remains unclear how well the classification systems would perform for hardwood species in other regions and forest types. Second, while current classification systems have demonstrated efficacy in modeling applications, their applicability often face a number of shortcomings. For instance, tree classification systems are often criticized for having too many categories or account for defects that do not necessarily have substantial impact on stem quality or vigor. This trend has been suggested by relatively insubstantial differences in product recovery or value across stem quality and vigor classifications (Havreljuk et al. 2014; Cockwell and Casperen 2015; Fortin et al. 2009). Finally, one of the substantial components that is not addressed in current classification systems is stem form. Although sweep or sinuosity is typically evaluated, the presence of other form characteristics such as significant forks and multiple stems are generally disregarded.

To address the deficiencies of the current stem quality and vigor classification systems, the Northern Hardwood Research Institute (NHRI) released a new protocol in 2014 to enhance silvicultural management of hardwood species in New Brunswick. The NHRI system builds upon the previous systems by integrating both metrics for stem form and vigor into a unified framework. Specifically, the NHRI system includes eight categories of form that account for stem straightness, lean, relative height of forks, and trees growing with multiple stems. The other component of the NHRI system is risk which is an assessment of tree vigor. There are four classifications of risk that are based on the presence and severity of multiple defects including significant forks, mechanical damage, animal damage, seams, cracks, cavities, rot and fungal infections. Although the NHRI system contains in aggregate 32 combinations of form and risk, it provides a comprehensive framework for testing the influence of a wider array of stem defects than current classifications systems.

Outside of Canada, predominant growth and yield models such as the Forest Vegetation Simulator (FVS) used in the Northeastern United States do not account for the influence of stem defects. The inability to account for the wide array of stem quality and vigor that hardwood species demonstrate could lead to potential bias in estimations of volume, growth, and mortality as evidenced by work carried out in Canada. In addition, further work is needed to develop more robust classification systems that can be used to effectively monitor and manage hardwood species in the Northeast region. To address these current limitations, the goal of this research was to build upon past work by evaluating the influence of stem form and risk on product potential, growth, and mortality using the NHRI classification system. The findings from this study will be used to refine the Acadian Variant of FVS (FVS – ACD) and develop a revised tree classification system.

CHAPTER 1

ASSESSMENT OF PRODUCT POTENTIAL AND OCCURRENCE OF STEM DEFECTS ACROSS NORTHERN COMMERCIAL HARDWOOD SPECIES

Abstract

Northern hardwood species display a wide variety of stem forms and defects which can considerably reduce stem quality and complicate the management objectives of these species. Although commonly cited as limiting factors of hardwood species, the influence of both stem form and damage remain largely unaccounted for in most growth and yield applications. In addition, the limited integration of these attributes into quantitative analyses has left the efficacy of current tree classification systems used to manage these species untested. Standing commercial hardwood tree species across 146 permanent plots in Maine and New Hampshire were assigned stem form and risk classifications using a system developed by the Northern Hardwood Research Institute (NHRI) of New Brunswick. Using the collected data in conjunction with a dataset provided by the NHRI, models were developed to; 1) quantify potential sawlog recovery as a function of tree size, form, and risk; 2) predict the occurrence of different stem forms and damage across hardwood species and site-specific variables. Results indicated that sweep, multiple stems, significant forks, and severe stem damage substantially reduced potential sawlog recovery. The occurrence of stem form and risk were found to be independent of the site-specific variables tested in the analysis and were instead best characterized as a function of species and tree size. Overall, the results highlight the range of hardwood stems form and risk across commercial species in this region as well as the importance of stem form and risk on potential product recovery and ultimately value.

Introduction

In the United States, northern hardwood forest types encompass approximately 8.1 million ha spanning from New York into portions of Canada adjacent to this region (Leak et al.

2014). Northern hardwood forest types are typically composed of sugar maple (*Acer saccharum* Marsh), red maple (*Acer Rubrum* L.), yellow birch (*Betula alleghaniensis* Britton), and American beech (*Fagus grandifolia* Ehrh.) but other species such as northern red oak (*Quercus Rubra* L.), aspen (*Populus tremuloides* Michx and ***Populus grandidentata*** Michx) and paper birch (*Betula papyrifera* Marsh) are commonly found as well. These species derive considerable economic impact as they have the potential to yield valuable veneer and saw timber products (Nyland 1998 and Cockwell and Casperen 2015). The importance of these species are reflected by recent trends in the forest product industry where in 2011, approximately 40% or 1.9 billion board feet of all harvested sawlog material harvested in Maine, New Hampshire, New York and Vermont was derived from hardwood species (NEFA 2013).

While capable of producing valuable wood products**,** hardwood species generally demonstrate a much greater range of product quality compared to softwood species (Cockwell and Casperen 2014). The variation in product quality results from the large variety of stem damage such as seams, cracks, rot, stain, and fungal infections (Cockwell and Casperen 2014; Drouin et al. 2010) as well as stem form characteristics including sweep, significant forks and multiple stems that hardwoods can demonstrate (Pelletier et al. 2013, Fortin et al. 2009). The impact of stem defects has been shown to reduce product value for several hardwood species by compromising internal wood quality or reducing product recovery. For instance, a variety of studies (e.g. Drouin et al. 2010; Belleville et al. 2011; Baral et al. 2013) have observed that the occurrence and extent of internal discoloration is much greater in birch and sugar maple species that demonstrate external stem defects. Reduction in sawlog volume for northern hardwood species is also common for those with extensive defects or poor stem quality (Cockwell and Casperen 2014, Fortin et al. 2009).

The range of stem quality and vigor in hardwood species can complicate the objectives of hardwood dominated or mixed-wood management where a common silvicultural treatment is selection cutting. Selection cutting systems intend to mimic small-scale mortality events through the removal of individual or small groups of trees in order to maintain mixed species and/or uneven-aged stand structures. From a management perspective the goal of this system is to simultaneously balance the objective of short-term profit while maintaining stands with future growing stock. However, given the large variety of stem quality and defects that hardwoods display, prioritizing which trees to harvest or retain can be quite challenging. Ultimately, failure to balance the objectives of selection management can lead to high graded stands that primarily contain low vigor trees (Pothier et al. 2013; Havreljuk 2014).

To facilitate the process of prioritizing trees for harvest, tree classification systems have been developed to characterize the significance of different defects that commonly arise on hardwood species. There are primarily four classification systems commonly used in the US and Canada; ABCD system, MSCR system, Acceptable Growing Stock (AGS)/Unacceptable Growing Stock (UGS) system, and Petro System. While these classification systems all evaluate stem defects on individual trees, their overall purpose can differ. For instance, the ABCD system and Perot system (Pelletier et al. 2013) evaluate a tree's stem quality in relation to product output and value while the MSCR and AGS/UGS system are predominantly used to assess a tree's vigor, which refers to its potential future growth and susceptibility to mortality (Guillimette et al. 2008; Hartmann et al. 2008**)**. The use of different tree classifications has shown to have important implications on predicting the presence of internal defects (Drouin et al. 2010), product recovery (Fortin et al. 2009; Cockwell and Casperen 2014; Schneider et al. 2008), and value for hardwood species (Cockwell and Casperen 2015; Havreljuk et al. 2014). Although proven useful in modelling applications, tree classification systems often face several criticisms. For example, these systems are often considered to have superfluous classes (Pothier et al. 2013) or emphasize defects which do not have significant implications on product value and recovery. Work by Cockwell and Casperen (2015) indicated that differences in net product value could be explained adequately using a hybridized stem quality and vigor system based on the ABCD and AGS/UGS systems as opposed to using each of these individually. Furthermore, Cockwell and Casperen

(2015) indicated that only a limited number of defects such as black bark, rotten wounds, cankers and cavities significantly impacted net product value. Similar findings from Havreljuk et al. (2014) also suggested that the identification of a few specific defects were capable of explaining almost as much variation in the value of sugar maple and yellow birch compared to the use of classifications from the ABCD and MSCR system. In addition to the need for more simplified systems, there is also evidence that the objectives of assessing stem quality and vigor should not be mutually exclusive from one another (Pothier et al. 2013; Cockwell and Casperen 2015). While some specific defects and stem quality classifications may be better suited for determining product value and recovery (Fortin 2009; Scheinder 2008; Cockwell and Casperen 2015), the use of vigor-based systems has improved predictions of growth and mortality (Fortin et al. 2008; Hartmann 2008). Since it is necessary for forest managers to derive short-term financial gain whilst fostering development of vigorous stands, consideration of defects that influence both of these objectives are essential.

The Northern Hardwood Research Institute (NHRI) released a new protocol in 2014 to enhance silvicultural management of hardwood species in New Brunswick (Pelletier et al. 2013). The NHRI system builds upon the previous systems by integrating both metrics for stem quality and vigor into a unified framework. Additionally, while previous stem classifications such as the ABCD and Perot system emphasized characteristics such as sweep and lean, the NHRI protocol places larger emphasis on wider range of stem forms. The focus on stem form in this system is expected to not only address product potential but also differences in harvesting cost for individual trees (Pelletier et al. 2013). Specifically, the NHRI system includes eight categories of form that account for stem straightness, lean, relative height of forks, and trees growing with multiple stems (Table 1.1). The eight form classes can also be organized into four groups based on their expected product potential: ideal form (F1), acceptable form (F2, F7), poor form (F5, F6, F8) and unacceptable form (F3, F4). As an example, trees of acceptable and ideal form are expected to yield more valuable product than trees classified as poor or unacceptable form. The other component of the NHRI system is risk, which is an assessment of tree vigor. There are four classifications of risk which are based on the presence and severity of different defects including significant forks, mechanical damage, animal damage, seams, cracks, cavities, rot and fungal infections (Table 1.2). Similar to the MSCR system (Hartmann et al. 2008; Havreljuk et al. 2014), the different degrees of risk relate to a trees future growth potential and susceptibility to mortality.

While it is commonly recognized that stem form and vigor can vary substantially among hardwood species, relatively little research has addressed how the occurrence of both these characteristics vary across different species, stand, and site conditions. Furthermore, most assessments of stem damage have focused only on specific defects (Burton et al. 2008; Giourd et al. 2008) or a relatively limited number of hardwood species (Pothier et al. 2013; Havreljuk et al. 2013, Westfall 2013). However, previous studies have provided important insight into the underlying factors accounting for variation in tree vigor. For example, crown ratio and diameter at breast height (DBH) have been shown to be important tree level attributes for predicting the extent of cull (Westfall 2013) or overall vigor in hardwood species respectively (Pothier et al. 2013). Metrics for stand density such as basal area and trees per hectare are also suggested to have a role in influencing individual tree vigor (Pothier et al. 2013; Baral et al. 2016). Relatively few studies have assessed site impact on tree vigor but recent work by Baral et al. (2016) indicated that stem quality decreased across higher quality sites as determined by the biomass growth index.

Table 1.1. Description of NHRI form classifications.

Form Class	Diagram	Description
F1		Ideal stem form. Single stem below 5 m. Maximum of 1 axes display curvature. Less than 15 degrees of inclination from main axis.
F2		Acceptable stem form. Single stem below 5 m. Less than 15 degrees of inclination from main axis. Sweep on 2 axes or 1 significant curve on the stem.
F3		Unacceptable stem form. Presence of large branches on the first 5 m. Large branches potentially carrying roundwood products.
F4		Unacceptable stem form. Multiple stems or branches on the first 5 m. Large branches have no potential for roundwood products.
F5		Poor stem form. Multiple stems are present between 0.3 and 1.3 meters of the stem.
F6		Poor stem form. Single stem in the first 5 m. Significant inclination of more than 15 degrees on the vertical axis.
F7		Acceptable stem form. Significant fork between 2.5 and 5 meters from the base of the tree. Large branches potentially carrying roundwood product.
F8		Poor stem form. Multiple stems present on the first 0.3 meters from the base of the tree.

Table 1.2. Description of NHRI risk classifications.

Risk Class	Description	Stem damage
R1 - Low risk	Very low probability of dying over the next 25 years.	Crook, sweep, white face scar, burl
R2 - Moderate risk	Low proability of dying between the next 15- 25 years.	Any of the above, frost cracks, small dark face scars, insect and animal damage, tree under high competition
R3 - High risk	Moderate probability of dying during next 5 - 15 years.	Any of the above, large open wounds, open splits
R4 - Very high risk	High probability of dying during the next 5 years.	Any of the above, fungal infections, black bark

The implications of stem form and damage on product distribution and output have not been extensively explored and in fact these features have generally been neglected in most work focused on volume estimation (MacFarlane and Weiskittel 2016). Recent work in Canada (Fortin et al. 2009, Cockwell and Casperen 2014) has indicated that classifications such as AGS/UGS and the ABCD system which characterize stem quality have demonstrated improvements of product recovery estimates in northern hardwood species. While both of these systems (AGS/UGS and ABCD) account for a large range of different defects, they largely ignore many of the stem form traits such as forks, multiple stems, and significant lean which are encompassed in the NHRI classification system. There is evidence that these specific form attributes could negatively impact product output of hardwood trees. For example, an analysis of lumber recovery in West Virginia suggested that trees displaying sweep reduced sawlog output for red oak and yellow poplar (*Liriodendron tulipifera* L.) (Lin et al. 2011). In addition, the presence of large forks on a tree's stem likely impact potential product as they have been shown to have significant implications on stem taper (MacFarlane and Weiskittel 2016).

Hardwood species have a substantial economic impact in the Northeastern United States and eastern Canada. A deeper understanding of the numerous defects that hardwoods can accrue is needed to facilitate management of these species. In order to assess the influence of stem form and vigor on hardwood trees, this study had three objectives; 1) evaluate product distribution across species, tree size, form and risk classes; 2) quantify the occurrence of stem form and risk across several different hardwood species and; 3) assess whether metrics of site condition contribute to the occurrence of different stem forms and extent of risk. Our hypothesis was that the proportion of sawlog volume will decline sequentially from trees with ideal form to those considered to have unacceptable form as defined in the NHRI protocol (Table 1.1). Similarly, sawlog volume is also expected to decline across the four risk classes (Table 1.2). The occurrence of poor stem form and damage is expected to vary across species and be frequent in sites considered to have lower quality.

Methods

Study area

The study was primarily conducted in the Acadian Forest Region which includes New Brunswick, Nova Scotia, Prince Edwards Island, Southern Quebec and Maine. Forests in this region predominantly consist of mixed species stands that have been shaped by selection harvesting and disturbance (Rijal et al. 2012). The primary forest types in this region include mixed conifers, mixed hardwood conifer forests, and wetland forest (Rijal et al. 2012).

Between 2013 and 2015, a total of 870 trees were destructively sampled by the NHRI in an effort to assess product recovery across several primary commercial hardwood species; red maple, sugar maple, yellow birch, and paper birch. These trees were collected on five sites that spanned four distinct eco-regions unique to New Brunswick; central upland, northern upland, highland, and grand lake. Elevations across the sites ranged from 140 to 373 m. Soils in these locations were generally well drained and consisted of Holmesville, McGee, Glassville, Lomond, and Sunbury types.

In 2015, standing tree measurements were taken on previously measured plots across the following five sites in Maine and New Hampshire: Austin Pond Research Forest, Holt Research Forest (HRF), Kingman Farms Research Forest, Penobscot Experimental Forest (PEF), and the Scientific Forest Management Area (SFMA). These locations encompassed a diverse range of forest types, stand and site conditions. Measurements were taken on both softwood and hardwood species however, the primary species of interest for this study consisted of: paper birch, aspen, red maple, red oak, sugar maple and yellow birch. Due to differences across sites, each one is described briefly below.

Penobscot Experimental Forest

The Penobscot Experimental Forest (PEF) is located in Bradley, Maine (44° 52' N, 68° 38'W). The soils in the PEF are largely dominated by poorly drained glacial till resulting from previous periods of glaciation. Forest composition of the PEF consists of northern conifers and hardwoods but are primarily dominated by spruce and fir species. Hardwood species are mostly comprised of red maple, paper birch, quaking aspen, big-tooth aspen, and gray birch (*Betula populifolia* Marsh) although, other species including, sugar maple, yellow birch, white ash (*Fraxinus americana* L.), black cherry (*Prunus seritona* Ehrh.) and northern red oak can also be found (Sendak 2003). There are 48 management units within the PEF that comprise three silvicultural experiments; the compartment management study, management intensity demonstration, and auxiliary selection cutting study. In this study measurements were taken in compartments undergoing the following silvicultural treatments, diameter limit cutting (MU 4, MU 15), commercial clear cuts (MU 8, MU 22), single tree selection cutting on a 10-year cutting cycle (MU 20), two-staged over story removal (MU 21) and reserve areas (MU 32A and MU 32B).

Austin Pond

Austin Pond is a study area located approximately 30 km northeast of Bingham, Maine (45.20°N, 69.70°W). The site is characterized by gently sloping outwash with soils ranging from Telos to Chesuncook series and two (good productivity) to 4(moderately poor productivity) on the Briggs (1994) soil drainage classification. Austin Pond also features a unique history of silvicultural treatments. Since its establishment in 1977, the site has been largely used to examine the efficacy of different herbicide treatments on early successional vegetation. In 1986, pre-commercial thinning was carried out on each half of previously established herbicide plots resulting in split plot treatments. The resultant split plot treatments characterize all combinations of competition release present on spruce-fir stands of large private landowners in Maine (Olson et al. 2012). Although the site is primarily characterized by spruce-fir forest type, a number of hardwood species including paper birch, quaking aspen, and red maple can be found there.

Holt Research Forest

The Holt Research Forest (HRF) is located in Arrowsic, Maine (44° N, 70° W) near the mouth of the Kennebec River. The climate of the HRF is characterized by warmer winters and cooler summers due to its proximity to the coast. Soils vary from shallow glacial deposits to deep glacial moraine sediments depending on the underlying topography. Forests on the HRF are mostly dominated by oak and pine stands with primary species being eastern white pine (*Pinus strobus* L.), red maple, northern red oak, and red spruce (*Picea rubens* Sarg.) (Schumann et al. 2003). The HRF property encompasses 120 ha of which 40 ha is composed of a contiguous grid of 1 ha plots which have been previously inventoried. Group selection based harvesting was carried out in 1988 within ten of the grids in the western portion (Kimball 1995) of the study area to enhance structural diversity and regeneration of pine and oak. No further harvesting operations have taken place on the HRF.

Scientific Forest Management Area

The Scientific Forest Management Area (SFMA) is located in the northern portion of Baxter State Park (46° N, 68° W). The topography of the SFMA generally consist of flat to rolling- hill terrain with elevation ranging from approximately 232-367 m. Features such as bogs and streams are also dispersed throughout the site. Soils in the area are for the most part well drained and largely consist of Ragmuff, Monarda, Chesuncook, Monson, and Telos soil types. Forest types in the SFMA mostly consist of pure softwood, however, a portion are comprised of a mixed softwood- northern-hardwood-forest type. Starting in the 1980s, the SFMA underwent intensive management and now approximately 66% of the total land base is managed while 14% is considered reserved and 15% is under riparian management. Of the land that is managed, the predominant silvicultural treatments are either even-aged or multi-aged shelterwoods.

Kingman Farms Research Forest

Kingman Farms Research Forest is a 137 ha parcel of land located in Madbury, New Hampshire (43° N, 71° W). The topography of the area is relatively homogeneous where the elevation only ranges from 37-43 m. Out of the 137 ha, 40 ha are dedicated to agricultural fields and the remaining 127 ha is composed of wetlands, meadows and woodlands. The soils in the area demonstrate relatively high productivity which consist of a wide variety of loamy soils. The wooded portion of Kingman farms property is composed of 13 stands that consist of some softwood species such as white pine and eastern hemlock but is mostly comprised of hardwoods such as red oak, maple, american beech, and birch species. The Kingman Farm property is not managed intensively and is primarily used for educational and research purposes.

Field Measurements

As part of an effort by the NHRI to evaluate product recovery for several northern hardwood species with varying stem form and risk, trees were destructively sampled across five sites in New Brunswick. Prior to felling, DBH and total tree height were measured using a diameter tape and digital hypsometer respectively. In addition, each tree was evaluated based on its stem form and vigor using the NHRI classification system. Once trees were felled, diameter measurements along each of the boles were made in varying increments following a procedure used to optimize bucking of logs. In addition, all logs received a classification from the Petro log grading system. Diameter measurements were taken until the approximate 8 cm top of each tree.

On every measurement site in Maine and New Hampshire, softwoods and hardwoods 10 cm and greater in diameter were assigned a NHRI form and risk class. In addition, the primary hardwood species of interest were assessed for product based on the principle of stick cruising where a trees stem is ocularly assessed in approximate 2.4 m sections. Each section received a product call of either sawlog potential, pulp or cull based on the extent and severity of defects on the section. Furthermore, the presence or absence of specific defects that were considered by the NHRI system was noted for all sections. Product calls were only made on the main stems of trees and did not take into consideration potential product in branches. The process of identifying products and defects was reiterated until the section that coincided with the approximate 10 cm top was reached. Criteria for determining product potential in standing tree were based on specifications presented in Rast (1973) and Cunningham et al. (2006). In order for a tree to contain at least one sawlog it had to have a minimum DBH of 25.4 cm with an approximated upper diameter of at least 20 cm. For trees considered to have multiple sawlogs, all appropriate sections were enumerated as sawlog potential until the approximate 20 cm top of the stem was reached. Sections meeting the size requirements of a sawlog but contained severe defects such as large open wounds, fruiting bodies, severe sweep, and significant forks were downgraded to pulp. As such, stem sections considered to be pulp material either did not meet the size specifications of sawlog material or contained defect(s) inhibiting it from being considered sawlog potential. Sections that did not meet either the sawlog or pulp size criteria and demonstrated such extensive defects that no foreseeable product could be derived from it were labeled as cull.

DBH measurements were taken for all hardwood and softwoods species using a diameter tape. Total tree heights, height to the first primary fork, and lowest live branch were obtained for approximately 20% of all the hardwood species of interest using a digital hypsometer. Trees with height measurements were sampled systematically to obtain a wide range of form and risk classes for each species.

Classifying trees using the NHRI system

The NHRI system consist of two components, form and risk which are used to assess a trees product potential and vigor respectively. Eight classes (F1 – F8, Table 1.1) are used to characterize stem form which are based on the straightness of a tree stem, inclination of stem from the main axis, and the presence and relative height of forks/multiple stems arising along the bole of a tree. Trees characterized with having undesirable form attributes such as significant forks and sweep are expected to have less potential product recovery. Tree vigor is assessed using four classes of risk (R1 – R4, Table 1.2) which is a determination of a trees future growth potential, product value and susceptibility to mortality. These classes are based on the presence and severity of a variety of different defects. For instance, trees determined to have high or very high-risk (R3 and R4 classifications) display visual evidence of severe wounds such as fruiting bodies, rot and large cavities while lower risk and moderate risk trees (R1 and R2) typically contain wounds not expected to substantially reduce vigor such as seams, scars and small open wounds.

Modelling saw log recovery

Data describing species sample size and the distribution across NHRI form and risk classes for the trees in both analyses are presented in Tables 1.3 and 1.4 respectively. Prior to model development, trees within both the Maine and New Brunswick datasets were inspected to ensure that diameter measurements and estimated proportions of sawlog volume were constrained to biologically reasonable limits. The distribution of species across form and risk classes was also examined (Table 1.4) to see if there were notable deficits of species/form and species/risk combinations. Quaking aspen trees were discarded from both analyses and paper birch was not included in the sawlog recovery analysis due to these species' limited occurrence across the eight NHRI form classifications (Table 1.4). In addition, only one tree was classified as F4 throughout both data bases and was subsequently merged into the F3 class since both of these form classes share similar characteristics (Table 1.1).

Product distribution in this study was evaluated as the proportion of estimated sawlog (m^3) to total merchantable volume (m^3):

[1] Proportion (Saw/Merch) = sawlog volume (m^3) / merchantable volume (m^3)

where sawlog volume is defined as the total amount of potential sawlog volume in a tree and merchantable volume encompasses the volume of a tree from stump height (0.3 m) to a 10 cm top. Sawlog volume for the trees sampled New Brunswick were derived by Smalian's formula using the destructively sampled log measurements:

[2] $\frac{A_1+A_2}{2} * L$

where A_1 is the area of the top of the log (m^2), A_2 is the area of the bottom of the log (m^2), and L is the length of the log (m). The volume of sawlog material for the trees sampled in Maine and merchantable volume for trees in both datasets were derived using the modified Kozak (2004) taper equation from (Li and Weiskittel 2012):

[3] d = $\alpha_0 D^{\alpha_1} H^{\alpha_2} X^{(\beta_1 z^4 + \beta_2 (1/e^{D/H}) + B_3 X^{0.1} + \beta_4 (1/D) + \beta_5 H^Q + \beta_6 X + \beta_7 I)}$

where d is diameter inside or outside of bark (cm), H is total tree height from ground (m), D is DBH (cm),

$X = 1 - z^{1/3} / 1 - p^{1/3}$, $Q = 1 - z^{1/3}$, h = section height from ground (m), p = 1.3/H (relative breast height) and z = (h/H) (relative height from ground). Since not all of the hardwoods in the Maine dataset have measured heights, these missing values were calculated through a plot-specific height imputation model. A modified version of the height imputation model developed in Robinson and Wycoff (2004) that included random intercepts terms for site and plot was used:

$$[4]\ h_{ijsk} = 1.37 + \exp\left(\alpha + b_i + b_j + \frac{\gamma}{2.54+d}\right) + \varepsilon$$

where b_i and b_j are random effects for ith plot and jth, site respectively, h is total tree height, d is diameter at breast height, α and γ are species specific coefficients. Once heights were derived for all trees in the data set, the height diameter ratio for each was calculated and used in subsequent analysis.

Table 1.3. Summary of trees sampled in Maine, New Hampshire, and New Brunswick

		DBH (cm)			
Species	No. of trees	Min	Mean	Max	SD
Paper birch	262	11.4	19.5	45.0	6.2
Quaking Aspen	245	11.4	21.8	49.5	8.9
Red maple	1301	11.4	21.7	74.0	7.9
Red oak	797	11.4	32.5	76.7	11.1
Sugar maple	555	11.7	28.5	82.0	11.3
Yellow birch	411	11.4	26.9	74.0	11.2

Table 1.4. Summary of species across NHRI form and risk classfications.

		NHRI form class							
Species	Risk	F1	F2	F3	F4	F5	F6	F7	F8
Aspen	R1	91	46	0	0	0	0	0	25
	R2	39	19	0	0	1	0	0	1
	R3	5	6	0	0	1	0	0	1
	R4	9	1	0	0	0	0	0	0
Paper birch	R1	58	54	0	0	3	3	1	22
	R2	26	45	0	0	8	2	10	8
	R3	6	5	1	0	1	0	1	0
	R4	4	2	0	0	0	1	0	1
Red maple	R1	154	50	0	0	12	1	0	194
	R2	215	61	1	0	50	8	28	161
	R3	84	25	4	0	22	4	10	35
	R4	80	19	2	0	28	3	11	39
Red oak	R1	58	54	0	0	15	4	0	29
	R2	211	116	0	0	78	5	41	83
	R3	16	9	0	0	3	1	2	12
	R4	22	13	0	0	10	1	1	13
Sugar maple	R1	83	9	0	0	0	0	0	14
	R2	175	18	8	0	16	19	26	35
	R3	33	13	1	0	7	5	5	4
	R4	46	5	5	1	6	2	2	7
Yellow birch	R1	44	25	0	0	11	0	0	8
	R2	88	34	9	0	23	5	33	15
	R3	18	17	8	0	7	3	8	3
	R4	16	15	4	0	0	2	10	5

Quantification of product recovery across northern hardwood species was conducted in two stages. First, analysis of covariance (ANCOVA) was used to assess statistical differences in recoverable sawlog material across NHRI form and risk classifications after accounting for tree size, species type and metrics of site quality (Table 1.5). Multiple comparisons between form and risk classes were performed using a pairwise Tukey's honestly significantly difference test (Tukey HSD). Differences between the form and risk group means were considered significant when $p < 0.05$. In order to determine if the NHRI system should be simplified, several aggregations of the full NHRI form and risk classes were developed. Three different form-class aggregations were created based on the following conditions: 1) a form classes expected product potential (F_1, Table 1.6), 2) biologically similar form attributes (F_2, Table 1.6) and 3) statistical differences observed in the preliminary ANCOVA, (F_3, Table 1.6). Only one aggregation of NHRI risk class was developed based on the extent and severity of tree damage where R1, R2 classes were separated from R3 and R4 classes (R_1, Table 1.6). Each of these aggregations were fitted in an ANCOVA framework and Tukey HSD tests were again used to detect significant differences between the group means of the form and risk aggregations. Once all multiple comparisons were performed, each of the ANCOVA models were evaluated in terms of their predictive capability.

Table 1.5. Explanatory variables used to develop models.

Variable	Description
Sp	Species type
DBH	Diameter at breast height (cm)
Ht	Total tree height (m)
HDR	Height diameter ratio
F_{NHRI}	NHRI form classifications
F_1	4 - class form aggregation based on product potential
F_2	4 - class form aggregation based on form characteristics
F_3	3 - class form aggregation based on Tukey comparisons
R_{NHRI}	NHRI risk classifications
R_1	2 - class risk aggregation based on Tukey comparisons
CSI	Climate site index for plot
Elevation	Elevation of plot (m)
Aspect	Aspect of plot (Radians)
Slope	Average slope of plot (%)
TWI	Topographic wetness index of plot
DC2	2 - class soil drainage indicator variable for plot
DC3	3 - class soil drainage indicator variable for plot
Lat	Latitude of site (decimal degrees)
Long	Longitude of site (decimal degrees)
Region	2 - class indicator variable representing sampling region (ME, NB)

To establish a predictive framework between the proportion of sawlog volume and the covariates of interest, a relationship between DBH and the proportion of sawlog volume was first developed. The following model form was used to link the proportion of sawlog volume to DBH:

$$[5]\ logit(S_{vol}/M_{vol}) = DBH + \ln(DBH)$$

where S_{vol}/M_{vol} is the ratio of sawlog volume to merchantable volume and DBH is diameter at breast height. The proportion of sawlog volume to merchantable volume was transformed using the logit function in order to compensate for skew in the data and achieve approximate normality in the error terms (Fox 2015). The logit transformation was preferred over the arcsine transformation since these values are much easier to interpret and all values between 0 and 1 produce relatively sensible predictions (Warton and Hui 2011). However, there were trees with no potential sawlog volume in the data set (ie. proportion of sawlog volume = 0), and a value of 0.001 was added to these to meet the criteria of the transformation.

Table 1.6. Descritption of NHRI form and risk aggregations.

New Group	Classes	Grouping criteria
F_1	1) Ideal form (ID) - F1 2) Acceptable form (AC) - F2, F7 3) Poor form (PR) - F5, F6, F8 4) Unacceptable form (UNAC) - F3, F4	Classes based on expected product potential
F_2	1) Single stem (SST) - F1, F2 2) Multiple stems (MST) - F5, F8 3) Low Fork (LF) - F3, F7 4) Significant lean (SL) - F6	Classes based on biologically similar form attributes
F_3	1) Good form (GF) - F1, F6 2) Acceptable Form (AF) - F2, F5, F8 2) Poor form (PF) - F3, F7	Classes based on tukey honestly significant difference tests.
R_2	1) Low risk (LR) - R1, R2 2) High risk (HR) - R3, R4	Risk classes based on severity of stem damage and statistically different tukey contrasts.

Data collected in this study had three distinct hierarchical levels (plots within sites, sites within region) thereby violating the assumption of independent and uncorrelated error terms. To address the hierarchical nature of the data, a mixed effects frame work was developed to account for correlated measurements and underlying variation across the different structural levels of the data (Uzoh and Oliver 2008; Robinson and Wycoff 2004). Likelihood ratio tests were used to evaluate a number of different random effects structures. Although the data had three levels of hierarchy, only random effects were included for site and plot. All random effect terms are assumed to be $N(0, \sigma^2)$. Mixed effects models were fit using the nlme package in R-statistical software (R Core Development Team 2016). Parameter estimates for fixed and random effects were derived using restricted maximum likelihood estimation (REML).

Modelling occurrence of stem form and vigor

Since the occurrence of a tree being high-risk or displaying a specific type of stem form attribute is binary, traditional multiple regression analysis using ordinary least squares could not be employed. Instead the presence or absence of these attributes was conducted using a series of multiple logistic regression models. The occurrence of vigor and different stem forms were assessed using the datasets from both Maine and New Brunswick where species, tree size, and several metrics of site quality were treated as independent variables (Table 1.5).

Occurrence of vigor was assessed by grouping R1, R2 (low risk = 0) and R3, R4 (high-risk = 1) classifications together. The aggregation of risk classes was determined based on findings from the ANCOVA in the sawlog recovery portion of the analysis and the fact that these groups separate trees logically based on their extent of risk (Table 1.6). The following model describes the probability of occurrence for a high-risk tree:

[6] $PR(HR) = \frac{e^{X\beta}}{1+e^{X\beta}}$

where PR(HR) is the probability of a tree being high-risk, and X is a vector of explanatory variables pertaining to the occurrence of high-risk trees.

Examination of the occurrence of different stem forms was performed using a three-class form aggregation (F_3, Table 1.6). Similar to risk, the different groupings of form were generated from classes that had the most impact on product recovery and biologically meaningful characteristics (F_3, Table 1.6). Specifically, the form classes under investigation comprised trees with single stems (F1, F6), extensive sweep (F2) or multiple stems (F5, F8), and significant forks on the first 5 m of their stem (F3, F7). Multinomial regression is commonly used to extend the binary logistic regression framework (Westfall 2013; Hosmer et al. 2013) where the dependent variable has multiple levels; however, this approach was not taken in this study due to the hierarchical nature of the data. A mixed effects framework was needed to address the different levels of the hierarchy, which cannot be readily extended to multinomial regression (Drouin et al. 2010). Instead, the following three logistic regression models were used to evaluate the occurrence of the three different stem form attributes:

[7] $Pr(GF) = \frac{e^{X\beta}}{1+e^{X\beta}}$

[8] $Pr(AF) = \frac{e^{X\beta}}{1+e^{X\beta}}$

[9] $Pr(PF) = \frac{e^{X\beta}}{1+e^{X\beta}}$

where Pr(GF), Pr(AF), Pr(PF) is the probability of a tree displaying either a single straight stem, extensive sweep or multiple stems, or low fork respectively and X is a vector of explanatory variables. Random effects were incorporated into all logistic model frameworks to account for the hierarchical nature of the dataset. The random effects structure was equivalent to the one presented in the sawlog recovery analysis where random intercept terms were included for site and plot effects. All logistic models were fit using the lme4 package in R-statistical programming environment (R Core Development Team 2016). Both fixed and random effects parameter estimates were derived using REML.

Model Selection and Evaluation

Stepwise - selection was used to determine which variables warranted inclusion in the final models used to assess recoverable sawlog volume and occurrence of stem form and risk. T-tests were used to assess the significance of individual parameters ($\beta = 0$), while Akaike information criterion (AIC) and likelihood ratio tests were used to evaluate if a variable was worth incorporating into a model. Consideration of biologically plausible parameter estimates was also taken into account.

Evaluation of model fit and performance differed as a consequence of the underlying distributions for models used to evaluate product distribution (Gaussian) and those used to predict the occurrence of stem form and risk (binomial). For the Gaussian models, residual plots were used to assess the assumptions of normality and constant variance of the error terms. Marginal and conditional R^2 (Nakagawa et al. 2013) were calculated to estimate the amount of variation explained by the fixed effects terms and random effects for each model using the MuMin package in the R statistical programming environment (R Core Development Team 2016). The precision and accuracy of the models was evaluated using root mean square error (RMSE) and bias (MB pred. – obs.).

For the binomial models, goodness of fit was determined by calculating the area under a receiver operator curve (AUC, ROC respectively) which is a plot of sensitivity versus 1-specificity (Hein and Weiskittel 2010; Hosmer 2013). AUC scores range from 0.5 – 1.0 where higher scores indicate a model with greater capability of discriminating if a subject experiences the given outcome of interest. According to Hosmer (2013), models with AUC scores between 0.5 – 0.7 have poor discrimination, those with 0.7-0.8 have acceptable discrimination, and models with scores greater than 0.8 are considered to have excellent discrimination. Generally, a cut point of 0.5 serves as a threshold to determine if a predicted probability signals the occurrence of an event. In this study an optimal cut point was selected using a technique implemented by Hein and Weiskittel (2010) where the probability threshold is determined through the maximization of the Youden index. For all logistic models the optimal cut point was derived using the OptimalCutpoints package in the R statistical programming environment (R Core Development Team 2016).

Results

Data used in subsequent analyses are presented in Tables 1.3 and 1.4 respectively. Out of the species sampled, red oak and red maple had the largest sample sizes. The range of size across the species was quite large and spanned from 11.4 to 82 cm (Table 1.3). The distribution of form and risk observations were highly variable which was in part due to the low sample sizes of some species as observed in Table 1.4. Among the species tested, red oak and red maple tended to have the largest number of poorly formed trees (F6, F5, F8), while maple species and yellow birch demonstrated the greatest number of high-risk trees.

Sawlog recovery

Multiple comparisons were carried out between form and risk classifications with DBH and species being the other independent variables in the ANCOVA framework. Among the seven form classes, differences were only significant ($p < 0.05$) between trees of ideal form and those displaying extensive sweep or a significant fork on the first 5 m of their stem (F1-F2, F1- F3, F1 – F7). Although not statistically significant, trees with multiple stems (F5, F8) appeared to have on average lower proportions of sawlog volume compared to trees with single stems that did not display extensive sweep or lean (F1, F6) as shown by least square means presented in Figure 1.1. Based on the statistical differences detected in the preliminary multiple comparisons and the visual discrepancies observed in Figure 1.1, a form aggregation with three classes (F_3, Table 1.6) consisting of the following form classes; good form (F1, F6), acceptable form (F2, F5, F8), and poor form (F3, F7) was developed. Further multiple comparisons for the three aggregations indicated that the proportion of sawlog volume was significantly lower for trees with poor and unacceptable form compared to those of ideal form using the aggregations based on expected product potential. Discrepancies in sawlog volume were more appreciable in form classes based on similar biological attributes (F_2, Table 1.6) where only sweep – multiple stems and sweep – low fork were not statistically different. All of the form classes in the F_3 aggregations were statistically differenct from one another. Compared to form classes, patterns in the proportion of expected sawlog between risk classes were much more distinct where high-risk trees (R3, R4) yielded significantly lower proportions of sawlog volume compared to low and moderate risk trees (R1, R2) (Figure 1.2).

Parameter estimates and model fit statistics are presented in Table 1.7 for the final model (Equation 1) that was developed to quantify sawlog volume recovery. As shown in Table 1.7, the proportion of sawlog to merchantable volume was a function of DBH, species, F_3, R_2 and two interactions between DBH, species, and risk. Overall the model did an adequate job of accounting for the variation in the response since Equation 1 had a marginal R^2 value of 0.45 when both the fixed and random effects were included (Table 1.7). However, the precision of the model was quite low, since on average the proportion of sawlog volume differed by 0.21 from the observed values as evidenced by its RMSE (Table 1.7). The bias of the model was relatively low although it did demonstrate a tendency to under-predict the proportion of sawlog volume (Table 1.7).

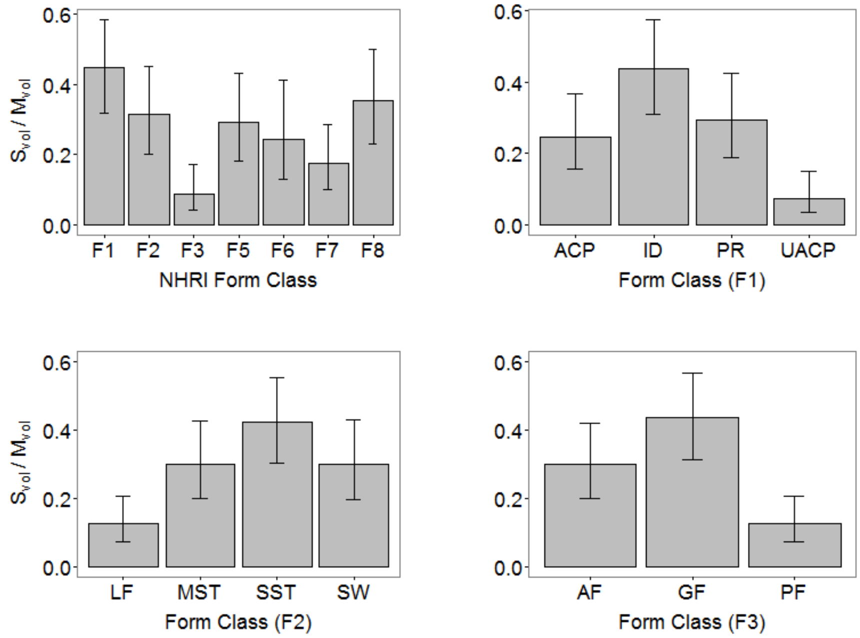


Figure 1.1. Least square means for NHRI form classes and F_1, F_2, and F_3 aggregations.

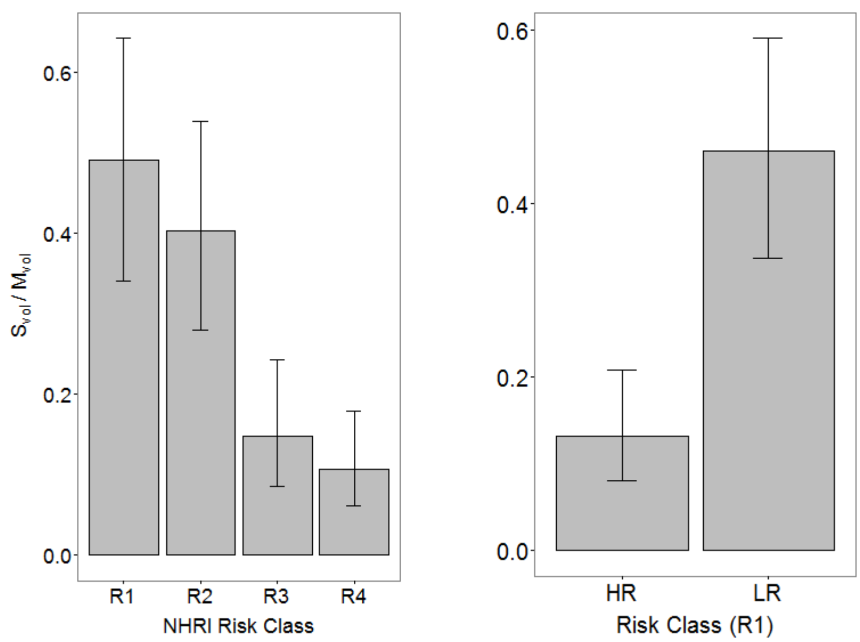


Figure 1.2. Least square means for NHRI risk classes and R_1 risk aggregation.

Predictions across species, form, and risk are presented in Figures 1.3 and 1.4 using Equation 1. All predictions shown were back transformed to the original scale using the inverse of the logit transformation:

$$[10]\ \frac{\mathrm{e}(S_{vol}/M_{vol})}{1 + e(S_{vol}/M_{vol})}$$

where S_{vol}/M_{vol} is the predicted proportion of sawlog to merchantable volume for an individual tree in the logit scale.

As shown in Figures 1.3 and 1.4, differences in sawlog volume across species was not substantial within the 25.4 – 35 cm DBH range. The proportion of sawlog volume increased more rapidly for red oak across DBH and demonstrated larger sawlog potential in larger diameter ranges (DBH > 40 cm). Once trees reached 40 cm in DBH the proportion of sawlog volume plateaued and began to decline with increasing DBH for all species other than red oak (Figure 1.3 and Figure 1.4). Differences in sawlog proportion were apparent across the form classes, where the proportion of sawlog volume was 70% higher for trees with good form compared to those with poor form (Figures 1.3 and 1.4). Overall the proportion of sawlog volume was much lower for high risk trees, particularly in lower diameter ranges (Figure 1.4). However, as DBH increased the differences in the proportion of sawlog material between high and low risk trees decreased (Figures 1.3 and 1.4).

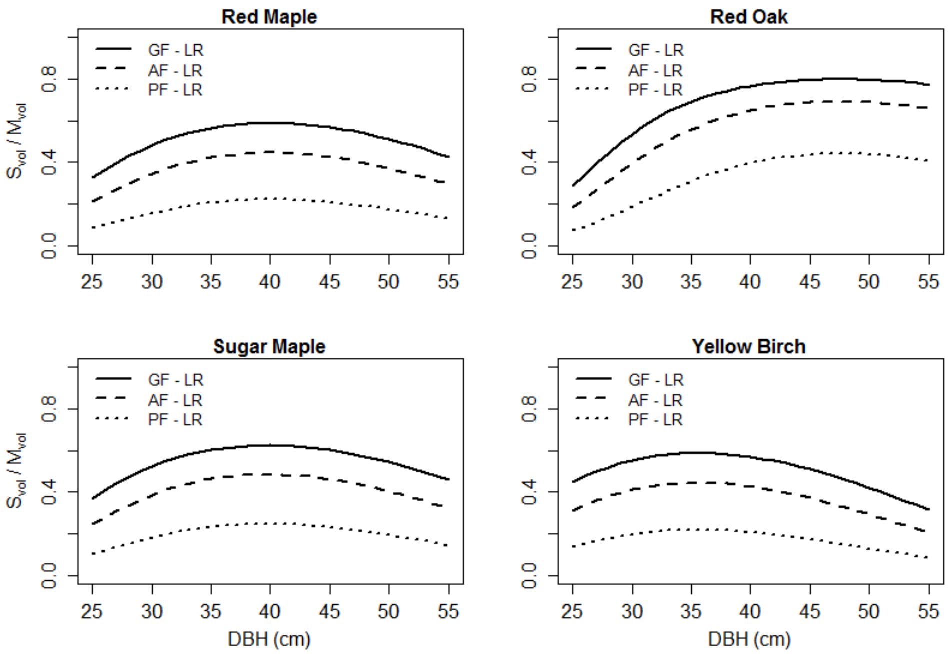


Figure 1.3. Predictions of S_{vol}/M_{vol} across species, form class, and low-risk trees. Predictions shown for red maple (top left), red oak (top right), sugar maple (bottom left), and yellow birch (bottom right).

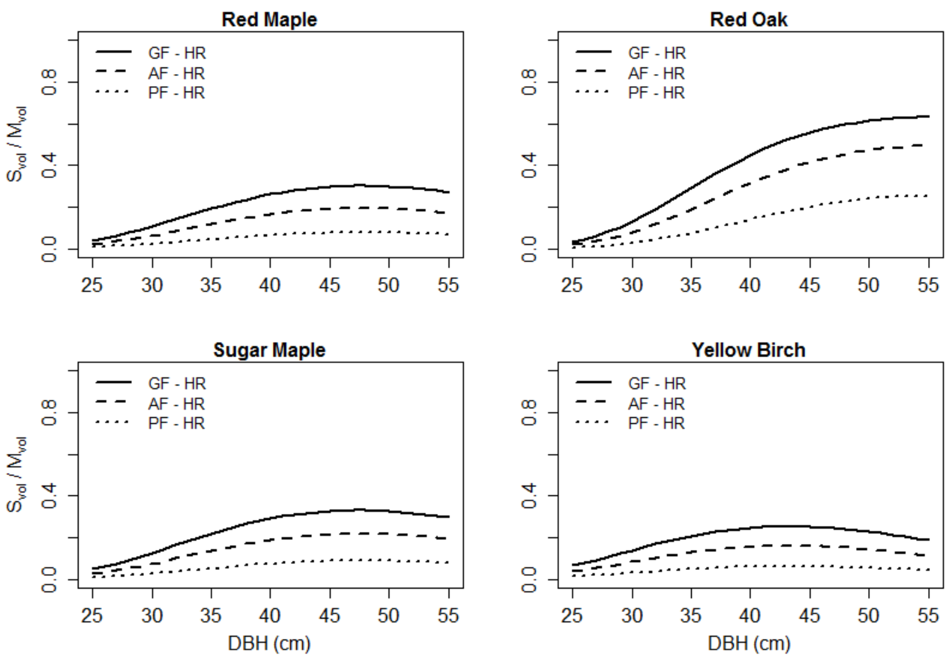


Figure 1.4. Predictions of S_{vol}/M_{vol} across species, form class, and high-risk trees. Predictions shown for red maple (top left), red oak (top right), sugar maple (bottom left), and yellow birch (bottom right).

Table 1.7 Parameter estimates and fit statsitics for saw log recovery model (Equation 1).

Parameter	Variable	Est	SE	Pr
β_0	Intercept	-40.6375	3.8568	<0.01
β_1	DBH	-0.2875	0.0344	<0.01
β_2	log(DBH)	13.6979	1.4	<0.01
β_{31}	Red oak	-7.1423	2.1857	<0.01
β_{32}	Sugar maple	0.4282	2.1911	0.847
β_{33}	Yellow birch	4.5696	2.4301	0.0604
β_{41}	GF	0.5701	0.0927	<0.01
β_{42}	PF	-1.0437	0.1572	<0.05
β_{51}	LR	9.5549	1.6469	<0.01
β_{61}	log(DBH) x LR	-2.2121	0.4629	<0.01
β_{62}	log(DBH) x Red oak	2.1633	0.6169	<0.01
β_{63}	log(DBH) x Sugar maple	-0.0754	0.6283	0.9045
β_{64}	log(DBH) x Yellow birch	-1.2606	0.6881	0.0672
Fit Statistics				
M-R^2	0.35	RMSE	0.21	
C-R^2	0.45	Bias	-0.05	

Occurrence of stem form and risk

Models to predict the occurrence of risk were developed using the two classes of risk from the sawlog recovery analysis. None of the site-specific factors tested in the analysis were found to be significant in the model framework (Table 1.8, Equation 2). Instead the probability of risk was best explained using a trees DBH, species type, and form class (F_3). A model which included these variables along with two-way interactions between DBH, species, and form (Table 1.8, Model 2) demonstrated the best model performance. The AUC score for the final model was 0.74 indicating that it could adequately discriminate between trees of high and low risk. As shown in Figure 1.5, the probability of a tree being higher risk appeared to follow a curvilinear pattern, where trees generally had a higher probability of being high-risk in lower DBH ranges (10 – 20 cm) but increased again once tree diameters approached approximately 50 cm (Figure 1.5). This pattern was more apparent for red maple and yellow birch compared to sugar maple and red oak species (Figure 1.5). Paper birch was the only species that did not follow the curvilinear trajectory but instead the probability of high-risk increased over its entire DBH range. Across the three form classes, the occurrence of high-risk trees was larger in lower DBH ranges but rapidly declined across tree size. However, the probability of damage did increase for larger trees with acceptable form.

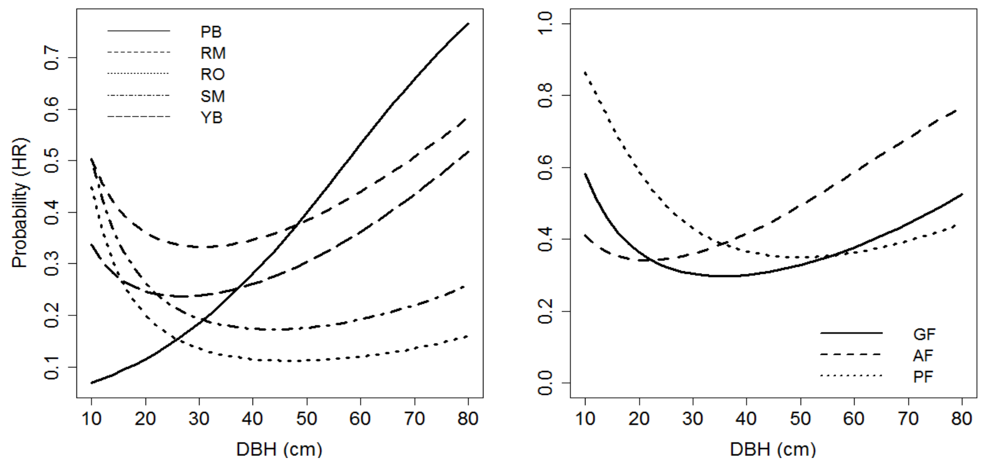


Figure 1.5. Probability of high risk trees across species (left) and form classes (right). Predictions of high trees across form classes are shown for red maple (right).

The occurrence of form was assessed using a three-class aggregation consisting of good, poor and acceptable form (F_3, Table 1.6). In general models only demonstrated acceptable discrimination as AUC scores for each ranged from 0.71 to 0.73 (Table 1.8, Equations 3 - 5). Similar to risk, the probability of a tree displaying a specific form class was independent of site characteristics (Table 1.8). The occurrence of form was influenced by species type and tree size. Interactions between DBH and species slightly improved AUC scores for prediction of trees with good or acceptable form but an additive model was sufficient for determining the occurrence of poorly formed trees (Table 1.8). Across the five species, sugar maple had the highest probability of having good form followed sequentially by red maple, yellow birch, red oak and paper birch (Figure 1.6). Paper birch had drastically higher probability of yielding trees of acceptable form, especially for those with larger diameters. In comparison, the likelihood of a tree displaying acceptable form declined across tree size for the other species (Figure 1.6). Finally, the differences in the probability of a tree being poorly formed across each of the species was not dramatic, although sugar maple and yellow birch tended to have higher probabilities of having a significant fork on the first 5 m of their stem (Figure 1.6).

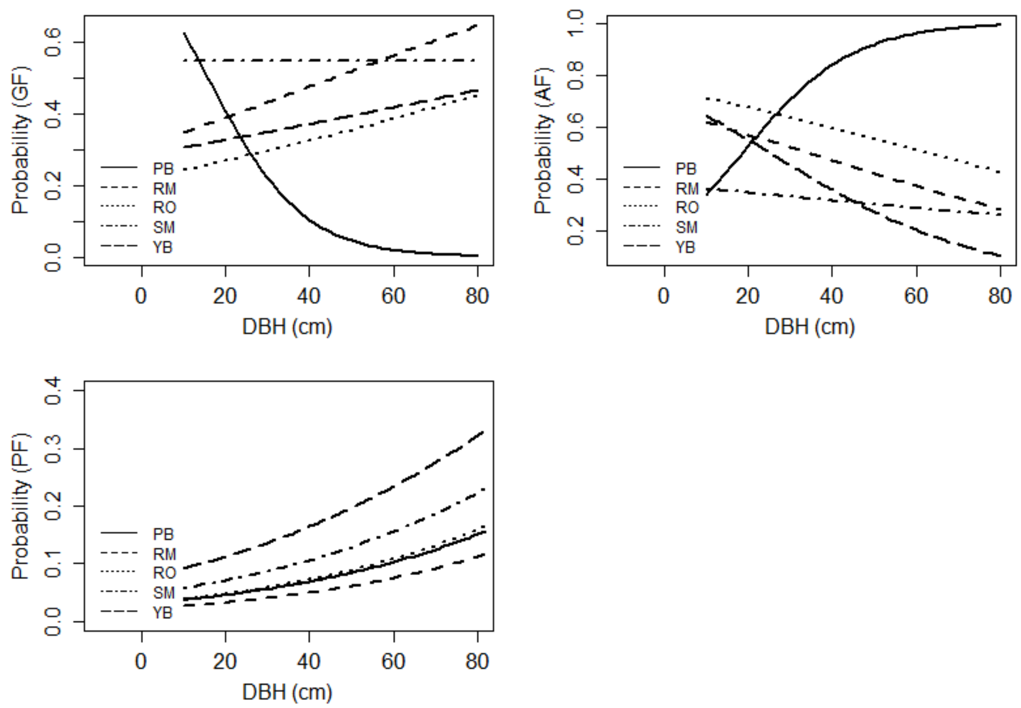


Figure 1.6. Probability of stem form occurence across species. Predictions are shown for GF (top left), AF (top right), and PF (poor form).

Table 1.8. Parameter estimates and fit statistics for occurrence of form and risk models (Equations 2 -5).

Model	Parameter	Variables	Est	SE	Pr	AIC	AUC
Equation 2	a_0	Intercept	-4.1312	2.5734	0.1084	3237.7	0.74
	a_1	DBH	0.0695	0.01998	<.01		
	a_2	log(DBH)	0.1980	0.8986	0.8256		
	a_{31}	Red maple	6.4400	2.3962	<0.01		
	a_{32}	Red oak	8.7629	2.5976	<0.01		
	a_{33}	Sugar maple	7.3968	2.5038	<0.01		
	a_{34}	Yellow birch	5.1352	2.5701	<0.05		
	a_{41}	GF	2.9984	0.8002	<0.05		
	a_{42}	PF	6.5601	1.4723	<0.01		
	a_{51}	log(DBH) x Red maple	-1.6620	0.7843	<0.05		
	a_{52}	log(DBH) x Red oak	-2.7088	0.8361	<0.01		
	a_{53}	log(DBH) x Sugar maple	-2.1597	0.8147	<0.01		
	a_{54}	log(DBH) x Yellow maple	-1.4247	0.8335	0.0874		
	a_{61}	log(DBH) x GF	-0.9492	0.2528	<0.01		
	a_{62}	log(DBH) x PF	-1.8350	0.4539	<0.01		
Equation 3	b_0	Intercept	-1.3927	0.5274	<0.01	4308.8	0.71
	b_1	DBH	-0.0822	0.0241	<0.01		
	b_{21}	Red maple	-2.1231	0.5191	<0.01		
	b_{22}	Red oak	-2.5143	0.5738	<0.01		
	b_{23}	Sugar maple	-1.3943	0.5699	<0.05		
	b_{24}	Yellow birch	-2.4247	0.5803	<0.01		
	b_{31}	DBH x red maple	0.0989	0.0249	<0.01		
	b_{32}	DBH x red oak	0.0939	0.0253	<0.01		
	b_{33}	DBH x sugar maple	0.0976	0.0256	<0.01		
	b_{34}	DBH x yellow birch	0.0997	0.0261	<0.01		
Equation 4	c_0	Intercept	-1.5455	0.5260	<0.01	4216.5	0.73
	c_1	DBH	0.0756	0.0232	<0.01		
	c_{21}	Red maple	2.1677	0.5101	<0.01		
	c_{22}	Red oak	2.5022	0.5662	<0.01		
	c_{23}	Sugar maple	1.3068	0.5777	<0.05		
	c_{24}	Yellow birch	2.7188	0.5829	<0.01		
	c_{31}	DBH x red maple	-0.0948	0.0240	<0.01		
	c_{32}	DBH x red oak	-0.0914	0.0244	<0.01		
	c_{33}	DBH x sugar maple	-0.1021	0.0253	<0.01		
	c_{34}	DBH x yellow birch	-0.1255	0.0258	<0.01		
Equation 5	d_0	Intercept	-3.5830	0.4176	<0.01	1463.7	0.73
	d_1	DBH	0.0169	0.0075	<0.05		
	d_{21}	Red maple	-0.4297	0.3265	0.1881		
	d_{22}	Red oak	0.0539	0.3801	0.8873		
	d_{23}	Sugar maple	0.5000	0.3763	0.1928		
	d_{24}	Yellow birch	0.8828	0.3521	<0.05		

Discussion

The proportion of estimated sawlog volume was best described as a function of DBH, species, form and risk along with two-way interactions between DBH, species and risk (Equation 1, Table 1.7). Estimated sawlog volume in a tree increased with DBH, which is a trend that has commonly been observed in numerous studies pertaining to volume estimation of hardwood species (Fortin et al. 2009, Cockwell and Casperen 2014, Lin et al. 2011). However, the extent of sawlog material in a tree eventually plateaued and began to decline once a certain diameter threshold was achieved (Figure 1.3). Different patterns in the diameter thresholds were observed among species resulting from significant interaction between species and DBH (Equation 1, Table 1.7). Red oak generally displayed a higher proportion of sawlog volume compared to the other species tested in the analysis (Figure 1.3 and Figure 1.4). In addition, red oak did not demonstrate a decline in sawlog volume that the others species did once DBH values reached 40 cm.

Meaningful differences in the proportion of sawlog volume were detected among form classes. However, the use of the eight NHRI classification system proved to be unwarranted since a reduced system with three classes adequately accounted for variation in sawlog volume among the hardwood species (F_3, Table 1.6). Findings similar to these have be suggested by previous work (Cockwell and Casperen 2015 and Havreljuk et al. 2014), which indicated that simplified classifications of stem quality were sufficient to account for differences in product value for yellow birch and sugar maple species.

In this study, average potential sawlog volume declined sequentially for trees characterized by extensive sweep or multiple stems (acceptable form) to those displaying significant forks on the first 5 m of their stem (poor form). Explanations for the reduction in sawlog volume for some of the influential form characteristics are more straightforward than others. For instance, there are several reasons why significant forks, particularly those occurring on the first 5 m of a tree stem, could strongly influence expected sawlog potential. The presence of a low fork can indicate a tree with a large crown ratio, which have been shown to have smaller heights even for trees of the same diameter (Jiang et al. 2007). Consequently, a shorter stem would likely lead to a reduction in overall volume. More recent work by MacFarlane and Weiskittel (2016) indicated that stem taper could decline dramatically resulting from the presence of a fork on the main stem. Reductions in sawlog proportion due to sweep was expected since significant stem curvature has potential to considerably reduce sawlog output (Lin et al. 2011). However, reductions in potential saw log material for trees with multiple stems were not as apparent based solely on ocular product estimates (Maine and New Hampshire) or log measurements (New Brunswick). It is possible that lower estimates of sawlog volume in these trees resulted from their tendency to demonstrate significant forks or sweep which are not accounted for in their respective NHRI classifications (F5, F8).

A trees level of risk was another significant factor that accounted for differences in potential sawlog material. Similar to form, the use of all four risk classes in the model framework did not improve predictions of estimated sawlog volume and was better characterized using just two classifications. Trees considered be high or very high-risk (R3 and R4) generally yielded overall much lower sawlog proportion values when compared to low and moderate risk trees (R1 and R2), although differences gradually diminished with increasing tree size (Figure 1.4). Identifying the specific drivers in volume loss resulting from risk was challenging due to the wide array of factors that these classifications encompass (Table 1.2). Across both regions, there were two reasons that likely accounted for product loss in high-risk trees. First, risk classifications distinguish a trees competitive status and thus reductions in sawlog volume could be attributed to trees with smaller boles as a result of being suppressed. The other probable cause for lower saw volume across risk classes is that the NHRI classification system assumes that significant forks, anywhere along a tree's stem, elevate risk. As such, risk could have a similar effect to that associated with poorly formed trees (fork(s) on the first 5 m of the main stem). A more thorough examination of the influence of stem damage could not be carried out since this information was not available for the trees sampled in New Brunswick. However, it can be postulated that reductions in sawlog volume were driven by severe defects such as open wounds, rot, or fruiting bodies which are indicative of high-risk trees (Table 1.2). Finally, it is important to note that part of the large discrepancy in sawlog volume between high and low risk trees was driven by trees expected to yield no sawlog ($S_{vol}/M_{vol} = 0$) due to extensive or severe defects on their stems.

The development of probabilistic models for assessing the occurrence of stem damage and vigor has not been extensively explored. The use of multilevel logistic regression in this study indicated that DBH, species, and form class were influential explanatory variables for predicting the occurrence of high-risk trees. Interestingly, the relationship of DBH among most of the species was curvilinear and for some, resembled the U-shaped pattern hypothesized for individual tree mortality (Adame et al. 2010; Monserud and Sterba 1999, Figure 1.5). The incidence of low vigor trees in small diameter classes is likely a result of suppression as risk classes take into account a tree's competitive status. The elevated probability of high-risk trees in the upper DBH range is most likely indicative of senescence and that these trees have been exposed to external forces (abiotic and biotic) for longer periods of time.

The results of this study also suggest that the occurrence of high-risk trees differed across the three form classes particularly in smaller diameter ranges with the exception of trees considered to be acceptable form (Figure 1.5). The greater occurrence of high risk trees for good and poor form trees could possibly be explained by suppressed trees, which have sustained minor wounds such as scarring or seams which would constitute a tree being high-risk (R3) according to the NHRI system. However, recent work has indicated that attributes such as large forks potentially serve as entry points for fungal pathogens that could subsequently lead to more severe damage such as decay (Baral et al.; 2013; Giroud et al. 2008). It has also been recognized that species growing in multiple stems as a result of stump sprout regeneration (Tubbs 1977; Smith 1997) could also be potentially more susceptible to decay, thereby providing a possible explanation for the higher incidences of low vigor trees with acceptable form.

There are numerous factors expected to influence a tree's stem form for hardwood species. The results of this study confirmed longstanding observations that hardwoods species demonstrate a large range of stem forms (Table 1.4). In fact, species was the most influential variable in all of the logistic regression models used to assess the occurrence of the three different form types. Explaining the differences in stem form occurrence among species is exceptionally difficult, as few previous studies have conducted comparative analyses of these form characteristics among hardwood species. One exception to this is that considerable work has been directed towards analyzing the occurrence of stump sprouting in hardwood species (Solomon et al. 1967; Keyser et al. 2014). The high occurrence of red maple and northern red oak with multiple stems likely resulting from stump sprouting (F5, F8) agree with previous findings from Solomon and Barton (1967) who observed that these species more frequently demonstrated stem sprouts when compared to sugar maple and birch species. Although the other physical attributes associated with poor and acceptable form classes (sweep and low forks) may be more prevalent for some species than others, the occurrence of these traits could also be controlled by genetic factors (MacFarlane and Weiskittel 2016) or stand conditions resulting from silvicultural treatments. For instance, practices such as thinning or others that reduce overall stand density can facilitate development of epicormic branches (Sonderman 1985, Marquis 1981). Management of species composition is also suggested to have implications on development of sweep and multiple stems as shown in a study of red alder (Grotta et al. 2004).

Conclusion

Quantitative models were developed to assess the impact of stem form attributes and defects on expected tree level product distribution using the NHRI classification system. Probabilistic models were also utilized to evaluate the occurrence of stem damage and form attributes across the northern hardwood species. The use of classifications of form and risk did improve predictions of recoverable sawlog volume. However, the implementation of the full NHRI system proved to be unwarranted for the purpose of product recovery since only three form classes and two risk classes were sufficient to explain the proportion of sawlog volume in individual trees.

The occurrence of high-risk trees and form attributes were independent of the site characteristics investigated in this analysis and were best described by species and tree size. There is likely a large array of factors such as management and stand level attributes (density, composition) that could better explain the differences in risk and form between the species. Unfortunately, information pertaining to these factors was not consistent in both datasets used in this study and could not be examined. Future work could likely improve assessments of both these attributes by incorporating metrics of stand characteristics and silvicultural treatments as explanatory variables.

Hardwood species will likely continue to play a large role in the forest industry of the Northeastern United States and Canada as they provide valuable saw timber. Management of these species is challenging though since they have large potential to develop many types of undesirable defects which can reduce their value. Based on the findings of this study, a simplified version of the NHRI classification system could help forest managers prioritize trees for harvest that could help balance the objectives of short term economic profit and long term retention of vigorous stands in selection cutting operations. In addition, this system’s ease of use could allow for it to be integrated into large scale forest inventories which could provide a better characterization of the hardwood resource at the regional scale. Acquisition of larger datasets that characterize stem characteristics of hardwood species would allow for further refinement of quantitative tools that could provide better projections of the resource.

CHAPTER 2

INCORPORATING STEM FORM AND RISK INTO PREDICTIONS OF INDIVIDUAL TREE GROWTH AND MORTALITY FOR SEVERAL NORTHERN COMMERCIAL HARDWOOD SPECIES

Abstract

Northern hardwood species display a wide variety of stem forms and defects which can considerably reduce stem quality and complicate the management objectives of these species. Although commonly cited as limiting factors of hardwood species, the influence of both stem form and damage remain largely unaccounted for in most growth and yield applications. In addition, the limited integration of these attributes into quantitative analyses has left the efficacy of current tree classification systems used to manage these species untested. The purpose of this study was to determine the influence of stem form and damage on growth and survival among several prominent northern commercial hardwood species and present a revised framework for a tree classification system. Standing commercial hardwood tree species across 146 permanent plots in Maine and New Hampshire were assigned stem form and risk classes using a system developed by the Northern Hardwood Research Institute (NHRI) of New Brunswick. Several models were developed to; 1) the regional Acadian Variant of Forest Vegetation Simulator (FVS-ACD) diameter increment equation as a result of trees with varying stem form and risk; 2) quantify the effect of form and risk on periodic annual increment and; 3) assess the influence of stem form on individual tree survival. The FVS-ACD diameter increment equation was found to over-predict for certain species and a binary classification of risk. Both reduced NHRI stem form and risk classifications were significant variables in the PAI diameter increment model but their effect was relatively small. Similar findings were observed for survival probability, which was only slightly lower for trees displaying multiple stems, significant forks, and multiple sweeps. Overall, the findings highlight the importance of stem form and risk on growth and survival

across multiple species in the region and suggest further classification of hardwood stems is needed.

Introduction

Northern hardwood and mixed-wood forest types account for approximately 8.1 million ha across the Northeastern United States and portions of Canada adjacent to this region (Leak 2014). The species in these forests provide considerable economic value as they have the potential to yield valuable veneer and saw timber products (Nyland 1998; Cockwell and Casperen 2015). The importance of these species are reflected by recent trends in the forest product industry where in 2011, approximately 40% or 1.9 billion board feet of all harvested sawlog material harvested in Maine, New Hampshire, New York and Vermont was derived from hardwood species (NEFA 2013). While capable of producing valuable wood products**,** hardwood species generally demonstrate a much greater range of product quality compared to softwood species (eg. Cockwell and Casperen 2014). Variation in product quality results from the fact that hardwood species are prone to a wide variety of stem damage agents such as seams, cracks, rot, and fungal infections (Cockwell and Casperen 2014; Drouin et al. 2010) as well as a greater range of stem form characteristics including sweep, significant forks and multiple stems (Pelletier et al. 2013; Fortin 2009). Although it has been commonly recognized that hardwood species are subject to a large array of defects, the integration of these features into silvicultural protocols and quantitative tools used to evaluate and project forest resources in the Northeast region has been limited.

The wide range of stem quality and vigor that hardwood species manifest can complicate the management objectives for hardwood dominated or mixed-wood forests, where a common silvicultural treatment is selection cutting. Selection cutting systems intend to mimic small-scale mortality events through the removal of individual or small groups of trees to maintain mixed species and/or uneven-aged stand structures (Hartmann et al. 2008; Pothier et al. 2013). From a management perspective the goal of this system is to simultaneously balance the objectives of short-term profit and retention of healthy stands for the future. Specifically, these objectives entail extracting merchantable volume and defective trees during each cutting cycle and leaving vigorous – low risk trees as future growing stock. However, given the large variety of stem quality and defects that hardwoods display, prioritizing which trees to harvest or retain can be quite challenging. Ultimately, failure to balance the objectives of selection management can lead to high-graded stands that primarily contain low vigor trees (Pothier et al. 2013; Havreljuk 2014).

To facilitate the process of prioritizing trees for harvest, a variety of tree classification systems have been developed which characterize the significance of different defects that commonly arise in hardwood species. Four classification systems have been used in the US and Canada: ABCD system, MSCR system, Acceptable Growing Stock (AGS)/ Unacceptable Growing Stock (UGS) system, and Petro system. While these classification systems all evaluate stem defects on individual trees, their overall purpose differ slightly. For instance, the ABCD and Perot system (Pelletier et al. 2013) evaluate a tree's stem quality in relation to product output and value while the MSCR and AGS/UGS system are predominantly used to assess a tree's vigor, which refers to its potential future growth and susceptibility to mortality (Guillimette et al. 2008; Hartmann et al. 2008**)**. Although proven useful in modelling applications (Fortin et al. 2009; Cockwell and Casperen 2014; Cockwell and Casperen 2015), tree classification systems often face several criticisms. For example, these systems are often considered to have superfluous classes (Pothier et al. 2013) or emphasize defects that do not have significant implications on product value and recovery. Past work by Cockwell and Casperen (2015) indicated that differences in net product value could be explained adequately using a hybridized stem quality and vigor system with three classes based on the ABCD and AGS/UGS systems as opposed to using each of these individually. Furthermore, Cockwell and Casperen (2015) indicated that only a limited number of defects such as black bark, rotten wounds, cankers and cavities significantly influenced net product value. In addition to the need for more simplified systems, there is also evidence that the objectives of assessing stem quality and vigor should not be mutually exclusive (Pothier et al. 2013; Havreljuk 2014; Cockwell and Casperen 2015). While some specific defects and stem quality classifications may be better suited for determining product value and recovery (Fortin et al. 2009; Scheinder et al. 2008; Cockwell and Casperen 2015), the use of vigor-based classification systems has improved predictions of growth and mortality (Fortin et al. 2008; Hartmann et al. 2008). Because forest managers often need to derive short term financial gain while fostering the development of vigorous stands, consideration of defects that influence both of these objectives are essential.

The Northern Hardwood Research Institute (NHRI) released a new protocol in 2014 to enhance silvicultural management of hardwood species in New Brunswick. The NHRI system builds upon the previous systems by integrating both metrics for stem quality and vigor into a unified framework. In addition, while the previous stem classifications such as the ABCD and Perot system emphasized characteristics such as sweep and lean, the NHRI protocol places a larger emphasis on a wider range of stem forms. The focus on stem form in this system is expected to not only address product potential but also differences in harvesting cost for individual trees (Pelletier et al. 2013). Specifically, the NHRI system includes eight categories of form that account for stem straightness, lean, height of forks, and trees growing with multiple stems (Table 2.1). The other component of the NHRI system is risk which is an assessment of tree vigor. There are four classifications of risk that are based on the presence and severity of multiple defects including significant forks, mechanical damage, animal damage, seams, cracks, cavities, rot, and fungal infections (Table 2.2). Similar to the MSCR system (Hartmann et al. 2008; Havreljuk et al. 2014), the different degrees of risk relate to a trees future growth potential and susceptibility to mortality.

Table 2.1. Description of NHRI form classifications.

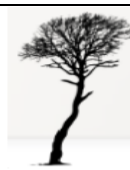
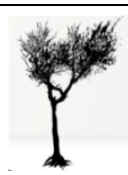
Form Class	Diagram	Description
F1		Ideal stem form. Single stem below 5 m. Maximum of 1 axes display curvature. Less than 15 degrees of inclination from main axis.
F2		Acceptable stem form. Single stem below 5 m. Less than 15 degrees of inclination from main axis. Sweep on 2 axes or 1 significant curve on the stem.
F3		Unacceptable stem form. Presence of large branches on the first 5 m. Large branches potentially carrying roundwood products.
F4		Unacceptable stem form. Multiple stems or branches on the first 5 m. Large branches have no potential for roundwood products.
F5		Poor stem form. Multiple stems are present between 0.3 and 1.3 meters of the stem.
F6		Poor stem form. Single stem in the first 5 m. Significant inclination of more than 15 degrees on the vertical axis.
F7		Acceptable stem form. Significant fork between 2.5 and 5 meters from the base of the tree. Large branches potentially carrying roundwood product.
F8		Poor stem form. Multiple stems present on the first 0.3 meters from the base of the tree.

Table 2.2. Description of NHRI risk classifications.

Risk Class	Description	Stem damage
R1 - Low risk	Very low probability of dying over the next 25 years.	Crook, sweep, white face scar, burl
R2 - Moderate risk	Low proability of dying between the next 15- 25 years.	Any of the above, frost cracks, small dark face scars, insect and animal damage, tree under high competition
R3 - High risk	Moderate probability of dying during next 5 - 15 years.	Any of the above, large open wounds, open splits
R4 - Very high risk	High probability of dying during the next 5 years.	Any of the above, fungal infections, black bark

Forest managers rely on growth and yield models to quantify forest resources and forecast potential outcomes of various management regimes (Lhotka et al. 2010; Fortin et al. 2008). While stand level models have historically been used to predict forest development, the use of tree level models has become more commonplace since they provide a more flexible framework for characterizing mixed species stands, competition, and silvicultural treatments (Kiernan et al. 2008; Weiskittel et al. 2011). In contrast to stand level models that are composed of a single equation (Fortin et al. 2008, Weiskittel et al. 2011), tree level models are comprised of several sub models. Two of the fundamental components of tree level models are diameter increment and mortality equations. Numerous diameter increment and mortality equations have been developed for hardwood and softwood species (Lhotka et al. 2010, Adame et al. 2008, Fortin et al. 2008) where explanatory variables usually account for tree size, social position, competition, and site quality. While models have accounted for vigor through metrics of crown size (Monserud et al. 1995, Weiskittel et al. 2007), stem form and other types of defects have largely not been incorporated into growth and mortality models. However, previous research has demonstrated that both of these factors can have important implications on predictions of individual tree growth and mortality. For example, work by Hann and Hannus (2002) noted that Pacific madrones (Arbutus menziesii Pursh) with multiple stems were 17% more productive in terms of five-year-diameter growth than individuals whose stems did not have significant forks. In addition, Fortin et al. (2008), indicated that a two class vigor system which accounted for crown dieback, cankers, and decay was found to be a significant variable in a diameter increment equation developed for northern hardwood species in Quebec. Further work by Fortin et al. (2008) indicated that probability of mortality was significantly higher for hardwood species that had been classified as low vigor in previous inventories. However, consistent with studies on product recovery (Havreljuk et al. 2014; Cockwell and Casperen 2015), it has been suggested that tree classification systems used to assess vigor and quality may contain unnecessary classifications for characterizing growth and mortality. In particular, this assertion was supported by Hartmann (2008) who indicated that only two out of the four classes in the MSCR classification system were sufficient to improve predictions of survival in sugar maple (*Acer saccharum* Marsh).

Hardwoods species have a significant role in the forest economy in the Northeastern United States and Canada. To facilitate successful management of these species, quantitative tools used in this region must accurately characterize their growth and mortality dynamics. Current growth and yield models used in the Northeast do not take into account the wide variety of stem form and damage that hardwoods can manifest which may consequently bias predictions of diameter increment and mortality. This study had three objectives; 1) assess whether there is bias resulting from stem form and risk in the commonly used regional diameter equation; 2) develop a periodic annual diameter increment model that accounts for form and risk, and; 3) determine whether stem form has a significant influence on individual-tree survival. Based on previous findings, it was hypothesized that diameter growth would be larger for trees with low significant forks (NHRI classification F7), multiple stems (NHRI classifications F5, F8), or excessive sweep (NHRI classification F2) compared to those with ideal form (NHRI classification F1) or significant lean (NHRI classification F6). In contrast to growth, the probability of mortality would be lower for trees with ideal form compared to all the other stem form classes. For risk, diameter growth was expected to decline across all four risk classes.

Methods

Study area

This study was primarily conducted in the Acadian Forest Region, which includes New Brunswick, Nova Scotia, Prince Edwards Island, Southern Quebec and Maine. Forests in this region predominantly consist of mixed species stands that have been shaped by selection harvesting and disturbance (Rijal et al. 2012). The primary forest types in this region include mixed conifers, mixed hardwood conifer forests, and wetland forest (Rijal et al. 2012).

In 2015 standing tree measurements were taken on previously measured plots across the following sites in Maine and New Hampshire: Austin Pond Research Forest, Holt Research Forest (HRF), Kingman Farms Research Forest, Penobscot Experimental Forest (PEF), and the Baxter State Park Scientific Forest Management Area (SFMA). These locations encompassed a diverse range of forest types, stand, and site conditions. Measurements were taken on both softwood and hardwood species; however, the primary species of interest for this study consisted of: paper birch (*Betula papyrifera* Marsh), quaking aspen (*Populus Tremuloids* Michx), red maple (*Acer rubrum* L.), red oak (*Quercus rubra* L.), sugar maple (*Acer sacchrum* Marsh), and yellow birch (*Betula alleghaniensis* Britton). Due to differences across site, each one is described briefly below.

Penobscot Experimental Forest

The Penobscot Experimental Forest (PEF) is located in Bradley, Maine (44° 52' N, 68° 38'W). The soils in the PEF are largely dominated by poorly drained glacial till resulting from previous periods of glaciation. Forest composition of the PEF consists of northern conifers and hardwoods, but is dominated primarily by spruce and fir species. Hardwood species are mostly comprised of red maple, paper birch, quaking aspen, big-tooth aspen, and gray birch (*Betula populifolia* Marshall) although, other species including, sugar maple, yellow birch, white ash (*Fraxinus Americana* L.), black cherry (*Prunus serotina Ehrh.*) and northern red oak can also be found (Sendak 2003). There are 48 management units within the PEF that comprise three silvicultural experiments; the compartment management study, management intensity demonstration, and auxiliary selection cutting study. For this study, measurements were taken in compartments undergoing the following silvicultural treatments, diameter limit cutting (MU 4, MU 15), commercial clear cuts (MU 8, MU 22), single tree selection cutting on a 10-year cutting cycle (MU 20), two-staged over story removal (Mu 21) and reserve areas (MU 32A and MU 32B).

Holt Research Forest

The Holt Research Forest (HRF) is located in Arrowsic, Maine (44° N, 70° W) near the mouth of the Kennebec River. The climate of the HRF is characterized by warmer winters and cooler summers due to its proximity to the coast. Soils vary from shallow glacial deposits to deep glacial moraine sediments depending on the underlying topography. Forests on the HRF are mostly dominated by oak and pine stands with the primary species being eastern white pine (*Pinus strobus* L.), red maple, northern red oak, and red spruce (*Picea rubens* Sarg.), (Schumann et al. 2003). The HRF property encompasses 120 ha with 40 ha composed of a contiguous grid of 1 ha plots that have been previously inventoried. Group selection based harvesting was carried out in 1988 within ten of the grids in the western portion (Kimball 1995) of the study area to enhance structural diversity and regeneration of pine and oak. No further harvesting operations have taken place on the HRF.

Scientific Forest Management Area

The Scientific Forest Management Area (SFMA) is located in the northern portion of Baxter State Park (46° N 68° W). The topography of the SFMA generally consist of flat to rolling- hill terrain with elevation ranging from approximately 232-367 m. Features such as bogs and streams are also dispersed throughout the site. Soils in the area are for the most part well drained and largely consist of Ragmuff, Monarda, Chesuncook, Monson, and Telos soil types. Forest types in the SFMA mostly consist of pure softwood, however portions are comprised of a, mixed softwood- northern-hardwood-forest type. Starting in the 1980s, the SFMA underwent intensive management and now approximately 66% of the total land base is managed, while 14% is considered reserved and 15% is under riparian management. Of the land that is managed, the predominant silvicultural treatments are either even-aged or multi-aged shelterwoods.

Kingman Farms Research Forest

Kingman Farms Research Forest is a 137 ha parcel of land located in Madbury, New Hampshire (43° N, 71° W). The topography of the area is relatively homogeneous where the elevation only ranges from 37-43 m. Out of the 137 ha, 40 ha are dedicated to agricultural fields and the remaining 127 ha is composed of wetlands, meadows and woodlands. The soils in the area demonstrate relatively high productivity which consist of a wide variety of loamy soils. The wooded portion of Kingman farms property is composed of 13 stands that consist of some softwood species such as white pine and eastern hemlock but is mostly comprised of hardwoods such as red oak, maple, beech, and birch species. The Kingman Farm property is not managed intensively and is primarily used for educational and research purposes.

Field measurements

At every measurement site, softwoods and hardwoods 10 cm and greater in diameter at breast height (DBH), were assigned a NHRI form and risk class. In addition, the primary hardwood species of interest were assessed for product potential based on the principle of stick cruising where a tree's stem is ocularly assessed in approximate 2.4 m sections. Each section received a product call of either sawlog potential, pulp or cull based on the extent and severity of defects on the section. In addition, the presence or absence of specific defects that were considered by the NHRI system were noted for all sections. Product calls were only made on the main stems of trees and did not take into consideration potential product in branches. The process of identifying products and defects was reiterated until the section that coincided with the approximate 10 cm diameter top was reached. Criteria for determining product potential in standing tree were based on specifications presented in past works of this topic (Rast 1973; Cunningham et al. 2006). In order for a tree to contain at least one sawlog it had to have a minimum DBH of 25.4 cm with an approximated upper diameter of at least 20 cm. For trees considered to have multiple sawlogs, all sections were enumerated as sawlog potential until the approximate 20 cm top of a stem was reached. Sections meeting the size requirements of a sawlog but contained severe defects such as large open wounds, fruiting bodies, severe sweep, and significant forks were downgraded to pulp. As such, stem sections considered as pulp material either did not meet the size specifications of sawlog material or contained defect(s) inhibiting it from being considered sawlog potential. Sections that did not meet either the sawlog or pulp size criteria and demonstrated such extensive defects that no foreseeable product were labeled as cull.

DBH measurements were taken for all hardwood and softwoods species using a diameter tape. Total tree heights, height to the first primary fork, and lowest live branch were obtained for approximately 20% of all the hardwood species of interest using a digital hypsometer. Trees with height measurements were systematically sampled to obtain a wide range of form and risk classes for each species.

Classifying trees using the NHRI system

The NHRI system consists of two components; form and risk that are used to assess a trees product potential and vigor respectively. Eight classes (F1 – F8, Table 2.1) are used to characterize stem form and are based on the straightness of a tree stem, inclination of stem from the main axis, and the presence and relative height of forks/multiple stems arising along the bole of a tree. Trees identified with undesirable form attributes, such as significant forks and sweep are expected to have less potential product recovery (Table 1.1). Tree vigor is assessed using four classes of risk (R1 – R4, Table 2.2) that provide a determination of a trees future growth potential, product value, and susceptibility to mortality. These classes are based on the presence and severity of a variety of different defects. For instance, trees determined to have high or very high-risk (R3 and R4 classifications) display visual evidence of severe wounds such as fruiting bodies, rot and large cavities while lower risk and moderate risk trees (R1 and R2) typically contain wounds not expected to substantially reduce vigor such as seams, scars and small open wounds (Table 2.2).

Modelling Diameter increment bias and periodic annual increment

The data for this study utilized diameter measurements obtained at various re-measurement intervals between 2001 – 2015 from permanent plot data in the Holt Research Forest, Kingman Farms Research Forest, Penobscot Experimental Forest and the Scientific Forest Management Area in Baxter State Park. Models fitted in this analysis included data from 146 plots for all trees ≥ 10 cm DBH. It is important to note here that sample sizes varied for each analysis in the study as a result of propagated measurement errors (trees with missing tags, no previous DBH values, etc.) in the inventory data. Descriptive statistics for tree level used to develop the diameter increment and mortality equations are presented in Tables 2.3 and 2.4 respectively. Plot level statistics are presented in Table 2.5.

Table 2.3. Summary of species across NHRI form classes.

Species	NHRI form class				
	(Live, Dead)	Mean DBH	SD DBH	Min DBH	Max DBH
Aspen	160	23.8	10.7	10.2	49.5
F1	(79, 16)	26.4	10.7	10.2	47.5
F2	(37, 7)	26.0	8.9	13.0	41.7
F5	(1, 0)	14.5	NA	14.5	14.5
F6	(0, 1)	18.3	NA	18.3	18.3
F7	(0, 1)	10.7	NA	10.7	10.7
F8	(16, 2)	13.5	1.2	11.9	15.2
Paper birch	252	20.0	6.7	10.4	43.2
F1	(71, 20)	18.7	6.9	10.4	37.0
F2	(81, 18)	20.4	7.0	10.4	39.1
F5	(9, 4)	20.2	4.3	12.2	26.0
F6	(5, 1)	20.2	6.7	11.7	28.0
F7	(9, 0)	21.3	9.9	12.2	43.2
F8	(22, 12)	20.2	4.9	13.2	30.2
Red maple	1046	19.1	6.6	10.0	56.4
F1	(382, 12)	19.7	6.6	11.7	54.1
F2	(118, 16)	20.1	6.2	10.0	41.9
F5	(74, 1)	21.9	9.5	12.0	56.4
F6	(12, 0)	22.1	8.0	12.7	34.8
F7	(41, 1)	18.4	5.7	11.7	35.1
F8	(379, 10)	17.6	5.9	10.2	47.5
Red oak	854	31.8	11.2	11.0	76.5
F1	(310, 7)	31.9	11.3	11.0	76.5
F2	(198, 8)	27.1	9.4	11.0	53.6
F5	(106, 15)	38.6	9.0	16.0	54.6
F6	(11, 1)	26.4	5.6	16.0	34.0
F7	(47, 0)	28.6	10.6	14.0	54.0
F8	(137, 14)	33.4	11.8	12.4	69.1
Sugar maple	184	23.4	11.5	10.7	64.8
F1	(117, 1)	23.1	11.2	11.7	64.8
F2	(18, 2)	27.7	14.4	11.4	60.0
F5	(10, 1)	21.7	9.7	12.7	43.2
F6	(4, 0)	41.6	5.7	35.6	48.8
F7	(5, 0)	24.3	14.5	14.5	40.9
F8	(23, 3)	18.6	7.1	10.7	34.8
Yellow birch	205	20.7	7.2	11.4	46.2
F1	(71, 2)	21.4	8.0	11.4	46.2
F2	(51, 3)	20.1	6.9	12.4	32.8
F5	(31, 0)	20.0	5.7	12.4	32.0
F6	(2, 0)	24.4	NA	24.4	24.4
F7	(24, 1)	23.3	8.7	11.7	46.0
F8	(19, 1)	17.8	4.8	12.0	29.0

Table 2.4. Summary of species across NHRI risk classes

	Risk Class			
Species	R1	R2	R3	R4
Aspen	77	35	12	9
Paper birch	105	82	7	7
Red maple	371	404	91	143
Red Oak	160	546	43	60
Sugar maple	34	89	22	32
Yellow birch	66	98	16	18

Table 2.5. Summary of stand level attributes.

Variable	Count	Min	Mean	Max	SD
Basal Area (m^2 ha^{-1})	147	6.0	27.2	68.0	11.5
Density (stems/ha)	147	205.0	700.6	1587.0	294.0
Crown Competition Factor	147	126.7	407.8	1114.0	157.5
QMD (cm)	147	12.5	22.7	41.4	5.1
BAL (m^2/ha)	2701	0.00	16.8	63.5	10.5

Assessment of the influence of form and risk in relation to diameter growth was conducted in two stages. First, potential bias of the current regional diameter increment equation in the Acadian Variant of the Forest Vegetation Simulator (FVS -ACD) was quantified to determine if there were any systematic patterns in predictions of annualized diameter increment resulting from trees with varying stem form and risk. The second phase of the analysis consisted of developing a diameter increment model to directly test the effect of form and risk on periodic annual increment (PAI) using DBH measurements from the 2015 inventory. In order to examine bias in the regional diameter increment model, annualized diameter increment values were derived using the regional diameter increment equation:

$$[1]\ DI_{pred} = \exp(\beta_0 + \beta_1 DBH + \beta_2 Spp\ x\ DBH + \beta_3 \log(CR) + \beta_4 \left(Spp\ x\ 1 - \frac{\frac{BAL}{BA}}{RS}\right) +$$

$$\beta_5 \log(CSI) + \beta_6 \sqrt[2]{BA\ x\ RS + 1} + \beta_7 BAL_{SW})$$

where DBH is diameter at breast height (cm), CR is crown ratio (%), BAL is basal area in trees larger than subject tree (m^2/ha^1), BA is stand level basal area (m^2/ha^1), RS is relative spacing, CSI is climate site index (m), and BAL_{SW} is basal area in trees larger than subject tree for softwood species (m^2/ha^1). Observed diameter increment from the 2015 inventory were calculated by the following:

[2] $DI_{obs} = DBH_{2015} - DBH_i$

where DBH_{2015} is diameter at breast height taken in 2015 and, DBH_i is diameter at breast height measurement from breast height from a previous inventory in year i. The extent of and direction of bias in the regional diameter increment equation was investigated by using the ratio of predicted diameter increment to observed diameter increment as the dependent variable:

[3] $DIR = (DI_{pred} * YIP) / (DI_{obs})$

where DIR is estimated diameter increment ratio, DI_{pred}, is predicted diameter increment, DI_{obs} is observed diameter increment and, YIP is the number of years between measurement periods. For development of diameter increment models, periodic annual increment was calculated by taking the difference between the diameter measurements in 2015 and previous diameter measurements and then dividing by the growth period ($[DBH_{2015} – DBH_i]$/ YIP).

Based on these data, two stages of model fitting were performed to evaluate bias in the regional diameter increment equation as well as models used to predict PAI. First, linear models were developed to establish the relationship between DIR, PAI, and various explanatory variables pertaining to tree size, competition, site quality, stem form, and risk. Models were first fit using all NHRI form (F1 – F8, Table 2.1) and risk classifications (R1 – R4, Table 2.2). Once suitable models were developed, multiple comparisons using pairwise Tukey's Honestly Significantly

Different tests were performed across form classes, risk classes, and species. The multiple comparisons were not only used to parse out significant form, risk and specie categories but also served as a means to aggregate any classes that were not statistically different from one another. Differences between form, risk and species means were considered significant when $p < 0.05$. After evaluation of multiple comparisons, models were then refitted to achieve the highest parsimonious and predictive capability.

Due to the hierarchical nature of the dataset (Sites/Plot/Year/Tree), several different types of random effects structures were tested during the model fitting process. The significance of random effects was evaluated using likelihood ratio tests ($p <0.05$). Although the data contained four potential hierarchical levels, the outcomes of the likelihood ratio tests indicated that random effects were only necessary to address variation across sites and plots. The following model frameworks were developed for this analysis:

[4] $\ln(DIR) = X\beta + Z\mu + \varepsilon$

[5] $\sqrt[2]{PAI} = X\beta + Z\mu + \varepsilon$

where X is the matrix of explanatory variables, and Z is the matrix of coefficients for the random effects accounting for site and plot. To meet the assumptions of linearity, normality, and homogeneity of variance in the error terms, transformations were performed on the response variables. The logarithmic and square root transformation were found to be most appropriate for DIR and PAI, respectively. All models were fit using the nlme package in the R-statistical programming environment (R Core Development Team 2016). Parameter estimates for fixed and random effects were derived using restricted maximum likelihood estimation (REML).

Modeling tree survival

Modeling mortality is generally a much different process than other components of individual tree growth and yield models since the dependent variable is a binary outcome (whether a tree died or not). Mortality can either be expressed as the probability of a tree dying or surviving over the course of a measurement period. The latter is desirable when the number of dead trees in a data set is much smaller in comparison to the number of living trees. This was the case for the dataset used in this study and as such probability of tree survival was expressed as the following:

[6] $\Pr(Survival) = \frac{1}{1+e^{\beta X}}$

where X is a vector of explanatory variables. With some algebraic manipulation (when trees are coded as, 1 = alive and 0 = dead, (Flewelling and Monserud 2002), Equation 6 can be expressed in the logistic form where:

[7] $\Pr(\text{Survival}) = \frac{e^{x\beta}}{1+e^{x\beta}}$

As a consequence of the binary response variable, common parameter estimation techniques such as ordinary least squares are generally not appropriate (Flewelling and Monserud 2002,). Instead logistic regression analysis is predominantly used to analyze data where the response is a dichotomous variable (Zhao et al. 2004; Monserud and Sterba 1999). While logistic regression provides a flexible and robust framework for quantifying the probability of tree survival, it does not perform as well when trees are measured across intervals of varying length (Flewelling and Monserurd 2002; Crecente-Campo et al. 2009). Since the measurement intervals for the dataset ranged from four to fourteen years, survival was calculated on an annualized basis using an approach introduced by Flewelling and Monserud (2002). In order to calculate survival on an annual basis, Equation 7 is rearranged as the following:

$$[8]\ \Pr(\text{Survival}) = \frac{\mathrm{e}^{x\beta}}{1+e^{x\beta}}^{\ YIP}$$

Where Pr(Survival) and X are previously defined and YIP is the number of years in the measurement period. Equation 8 was fitted using nonlinear model fitting techniques. Random effects were incorporated into the model framework to account for the hierarchical nature of the dataset. The random effects structure was equivalent to that used in the diameter increment models, where random intercept terms were included for site and plot effects. Models were fit using the nlme package in the R-statistical programming environment (R Core Development Team 2016). Both fixed and random effects parameter estimates were derived using REML.

Model Variable Selection

It has been established in numerous studies that both survival (or mortality) and diameter increment can be influenced by tree size, competition and site quality (Weiskittel et al. 2011; Adame et al. 2008; Zhao et al. 2004). Thus, in addition to NHRI form and risk classifications, the following variables were tested in both diameter models (bias and PAI) and tree survival models:

(1) Tree size: DBH is the most commonly used variable to express tree size in diameter increment and mortality equations. For this study DBH was the only metric of tree size that was used. It has been demonstrated frequently in past studies that diameter increment follows a peaking behavior across DBH where it increases across trees of smaller diameters, plateaus, and then decreases across larger sized trees (Zhao et al. 2004; Uzoh et al. 2008). For mortality, DBH is hypothesized to follow U-shaped pattern across diameter where the

probability of mortality is large in lower diameter ranges, declines across mid-ranged diameter classes, and increases again for larger diameters as a result of senescence (Monserud and Sterba. 1999; Temesgen et al. 2005). Consequently, the logarithmic, squared, square root and inverse transformations were tested in the model framework to account for the nonlinearity in DBH for diameter growth and mortality.

(2) Competition: Metrics of competition in diameter increment and mortality models generally account for both two-sided and one-sided competition. Two-sided competition accounts for competitive pressure that all trees exert on each other for site-specific resources such as light, water and soil nutrients (Adame et al. 2008). One-sided competition on the other hand, addresses an individual tree's competitive status within a stand (Lhotka et al. 2010). Variables accounting for two-sided competition included stand basal area (m^2 ha^{-1}), stems per ha, crown competition factor (CCF), relative density (RD) and relative spacing (RS) (Table 2.5). Basal area in larger trees (BAL, m^2 ha^{-1}) and several modifications of this variable including BAL/BAHA and BAL/DBH were tested to address one-sided competition.

(3) Site quality: A combination of continuous and categorical site quality variables were tested. Continuous variables included: climate site index (CSI), latitude/longitude (LAT, LONG), elevation (m), slope (%). mean annual temperature (°C), mean annual precipitation (mm), mean growing season temperature (°C) and mean annual precipitation (mm). Categorical site variables accounted for physiographic characteristics including soil type and soil drainage class.

Stepwise - selection was used to determine which variables warranted inclusion in the final models for diameter increment bias, periodic annual increment, and survival. T-tests were used to assess the significance of individual parameters (β= 0), while Akaike information criterion (AIC) and likelihood ratio tests were used to evaluate if a variable was worth incorporating into a model. Consideration of biologically plausible parameter estimates were also taken into account.

Model selection and evaluation

Several metrics of fit were used to develop final model forms for the growth models. Residual plots were first used to assess the assumptions of normality and constant variance of the error terms. Marginal and conditional R^2 values (Nakagawa et al. 2013) were calculated to estimate the amount of variation explained by the fixed effects terms and random effects for each model using the MuMin package in the R statistical programming environment (R Core Development Team 2016). The precision and accuracy of the models was evaluated using root mean square error (RMSE) and bias (MB, pred. – obs.).

Additional model evaluation criteria were used to assess if the final model for estimation of diameter increment bias could be used to improve upon the predictive capability of the regional equation. Based on the significant variables in the final model, correction factors (ratio of DI_{pred}/DI_{obs}) were developed from the model and applied to the predicted diameter increment using the following procedure:

[9] $DI_C = DI_{pred} / CF$

To obtain DI_C on an annualized basis:

[10] $ADI_C = DI_C / YIP$

where DI_C is corrected diameter increment predictions from FVS-ACD, CF is the correction factor derived from the final model, and ADI_C is corrected annualized diameter increment from FVS-ACD. Efficacy of the correction factors was determined by deriving (MB) and RMSE between corrected annualized diameter increment and observed periodic annual increment as follows:

$$[11]\ \text{RMSE} = \frac{\sqrt[2]{n \sum_{n}^{1} ADIc - PAI}}{n}$$

$$[12]\ \text{MB} = \sum_{n}^{1}(ADI_C - PAI_{obs})$$

where PAI_{obs} is observed periodic annual increment and ADI_C is previously defined. Corrected RMSE and bias were compared against RMSE and MB for uncorrected annualized values.

For the survival models, goodness of fit was determined by calculating the area under a receiver operator curve (AUC, ROC respectively) which is a plot of sensitivity versus 1-specificity (Hein and Weiskittel 2010; Hosmer 2013). AUC scores range from 0.5 – 1.0 where higher scores indicate a model with greater capability of discriminating if a subject experiences the given outcome of interest. According to Hosmer (2013), models with AUC scores between 0.5 – 0.7 have poor discrimination, those with 0.7-0.8 have acceptable discrimination, and models with scores greater than 0.8 are considered to have excellent discrimination. Frequently, a cut point of 0.5 serves as a threshold to determine if a predicted probability signals the occurrence of an event. In this study an optimal cut point was selected using a technique implemented by Hein and Weiskittel (2010) where the probability threshold is determined through the maximization of the Youden index. For all of the survival models the optimal cut point was derived using the OptimalCutpoints package in the R statistical programming environment (R Core Development Team 2016).

Results

Assessment of bias in the regional diameter increment equation

The model used to predict bias in the regional diameter increment equation consisted only of species and risk class as explanatory variables (Table 2.7, Equation 1). None of the tree size, competition or site quality variables were found to be significant suggesting that the regional equation adequately accounted for these factors. Multiple comparisons across species revealed that differences in the ratio of predicted diameter to observed diameter increment for northern red oak was 29% (Figure 1, $p < 0.05$) lower than the other species in the dataset (quaking aspen, paper birch, red maple, sugar maple and yellow birch). Subsequently, all the other species were aggregated into one group (indicated by OH for other-hardwood species; Figure 2.1).

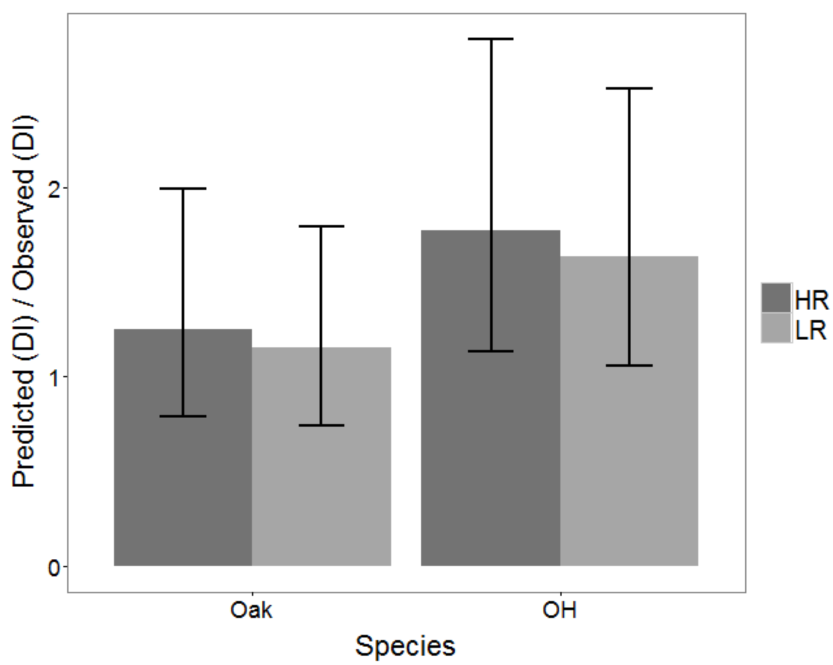


Figure 2.1. Predicted DIR by species and risk class. LR and HR are low and high-risk, respectively. Other hardwoods (OH) included aspen, paper birch, red maple, sugar maple, and yellow birch.

All four of the risk classes (R1 – R4) in the NHRI classification system were not found to be statistically significant from one another. Instead risk classes were aggregated into groups consisting of either low or high-risk trees (LR = R1 and R2, HR = R3 and R4). Although the groupings allowed for a more parsimonious model, the average ratio of predicted to observed diameter was only 8% larger for high-risk trees and only marginally significant ($p = 0.07$). Overall the model fit was poor as evidenced by the low marginal and conditional R^2 values shown in Table (2.8). The model also demonstrated poor precision and tended to underestimate the ratio of predicted to observed diameter increment as demonstrated by its RMSE and MB (Table 2.7).

The correction factors for species and risk are presented in Figure 2.1 and fit statistics for corrected ADI are presented in Table 2.6. Overall, mean bias did not improve once correction factors were applied to the predicted annualized diameter increment predictions from the regional model. Only predictions of low and risk red maple and yellow birch showed small improvement in terms of accuracy as shown by their reduced MB (Table 2.6). Precision in predicted diameter increment improved for most species as RMSE were reduced once correction factors were applied (Table 2.6). The only species that did not show improvement were aspen and low risk sugar maple.

Table 2.6. Fit statistics for uncorrected (UC) and corrected (C) annualized diameter increment. Mean bias (MB) and root mean square error (RMSE) are shown across species and risk.

	Low risk		High risk	
Species	MB	RMSE	MB	RMSE
	(UC, C)	(UC, C)	(UC, C)	(UC, C)
Aspen	(0.0473, -0.1087)	(0.1331, 0.1410)	(0.0047, -0.1591)	(0.1669, 0.1669)
Paper birch	(-0.0019, -0.1000)	(0.1556, 0.1526)	(-0.1400, -0.2407)	(0.3710, 0.3305)
Red maple	(0.0610, -0.0592)	(0.1424, 0.1229)	(0.0923, -0.0444)	(0.1648, 0.1193)
Red oak	(0.0128, -0.0269)	(0.1546, 0.1463)	(-0.0103, -0.0729)	(0.1897, 0.1782)
Sugar maple	(-0.0607, -0.1709)	(0.2100, 0.2134)	(0.0047, - 0.1591)	(0.1669, 0.1221)
Yellow birch	(0.0731, -0.0461)	(0.1744, 0.1431)	(0.1000, -0.0463)	(0.1730, 0.1453)

PAI model

PAI was expressed as a function of DBH, species type, BAL, form, risk, climate site index and an interaction term between DBH and species (Table 2.7, Equation 2). With the exception of the interaction, all parameter estimates were highly significant ($p < 0.05$). Although the interaction was not significant, it was retained in the model framework as it more accurately characterized PAI across species than a purely additive model. In comparison to the majority of past studies that have focused on diameter increment models, the unimodal positively skewed shape across diameter was not observed. Instead the trend in diameter was best explained by the logarithmic transformation of DBH. Interestingly, two-sided competition was also not found to be a significant variable. While most of the metrics of two-sided competition did display appropriate signs (negative) during the model fitting process, they did not achieve an appropriate significance level ($\alpha = 0.05$).

Multiple comparisons across species indicated that average PAI for red oak was significantly higher than all other species. Rather than aggregate species based on the outcomes of the multiple comparisons, species were instead grouped into three classes consisting of intolerant hardwoods (aspen and paper birch), oak (northern red oak), and tolerant northern hardwoods (red maple, sugar maple, and yellow birch). This aggregation allowed for a more parsimonious model and helped account for the uneven distribution of form and risk classes across species (Table 2.3 and Table 2.4). Differences were not statistically significant between all six of the form classes but PAI was statistically higher for trees with single straight stems (F1), low significant forks (F7), or multiple stems (F5, F8) compared to those with multiple sweeps (F2) or lean greater than 15% (F6).

Similar to form, not all of the risk classes were statistically different from one another ($p < 0.05$). Risk was grouped into two classes consisting of high-risk (HR = R3 and R4) and low risk trees (LR = R1 and R2) where high-risk trees demonstrated statistically lower PAI values compared to low risk trees. As a result of the high variability in PAI, the fixed effects of Equation

2 only explained 15% of the variation in the response (Table 2.8). The model also demonstrated low precision as shown by its RMSE value in Table 2.8, but it was relatively unbiased.

Using only the fixed effects from Equation [2] (Table 2.7), periodic diameter increment predictions were obtained and back-transformed by squaring the predicted values. Predictions are shown across diameter and the three species groups in Figure 2.2. The effects of form and risk classes are presented in Figure 2.3 for northern oak. For all predictions BAL and CSI were held constant at their mean values of 17 (m^2 ha^{-1}) and 16 m respectively. Periodic diameter increment was highest for red oak species and sequentially declined in magnitude from tolerant to intolerant hardwoods. For high-risk trees the average PAI was 22% lower than low risk trees (Figure 2.3). Trees with in form class A had 14% higher PAI rates compared to those with of form class B (Figure 2.3).

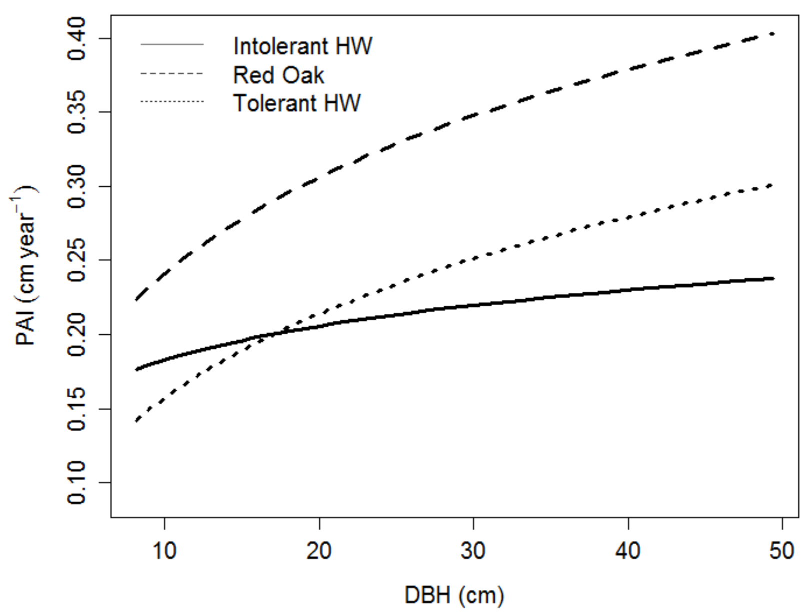


Figure 2.2. Periodic annual diameter increment predictions across species. Predictions of PAI are shown (cm yr^{-1}) over diameter at breast height (DBH; cm) across species with climate site index (CSI) and basal area of larger trees (BAL) held at 16 m and 17 m^2 ha^{-1}, respectively.

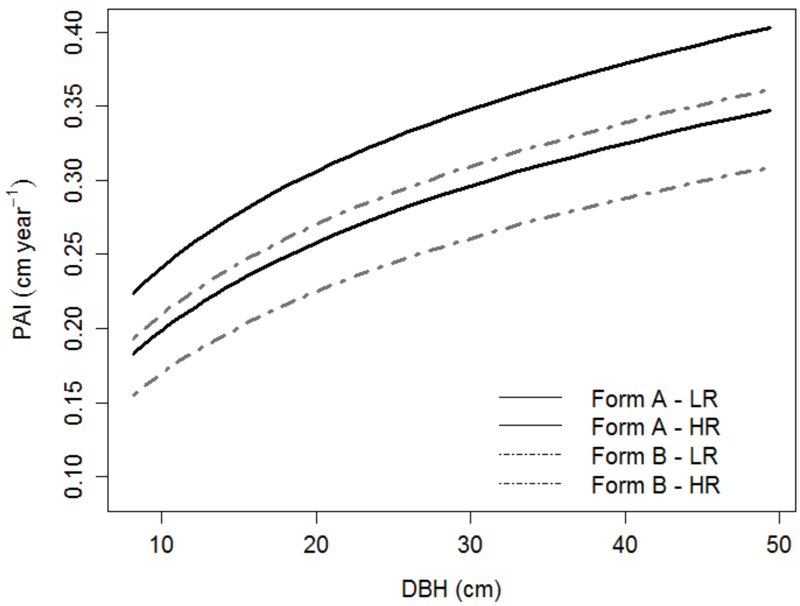


Figure 2.3. Periodic annual increment predictions across form classes. PAI predictions are shown (cm yr^{-1}) over diameter at breast height (DBH; cm) for northern red oak across various form and risk classes. Climate site index (CSI) and basal area of larger trees (BAL) were held at 16 and 17 m^2 ha^{-1}, respectively. Form class A is trees of ideal form (NHRI form class F1), while form class B is tree of poor form (NHRI form classes F2-F8). LR and HR are low and high-risk, respectively.

Survival model

The explanatory variables used to explain annual tree survival consisted of DBH, BAL, species (Intolerant hardwoods, oak, tolerant hardwoods), and form (Equation 3, Table 2.7). All variables in Equation 3 were significant at (p <0.05). and demonstrated biologically logical estimates. Species were aggregated into the same groups used in the diameter growth models, which consisted of tolerant hardwoods, oak, and intolerant hardwoods. Multiple comparisons across form indicated that form classes could be aggregated into two classes, where trees of ideal form (A = F1) were separated from the remaining five NHRI form classes (B = F2, F5, F6, F7 and F8) observed in the dataset. The difference in survival rates between both form classes were statistically significant (p <0.05). Overall the model performed well as the AUC score was 0.82 indicating excellent discrimination between live and dead trees (Table 2.8).

Predictions of annualized, individual-tree survival probability across DBH, species and form are shown in Figure 2.4. All predictions were made using Equation 3 (Table 2.7) while holding BAL at its mean value (17 m^2 ha^{-1}) and YIP at a one-year time step. Annual tree survival increased across diameter for all species, although the intolerant hardwood species appeared to demonstrate a somewhat more gradual ascent (Figure 2.4). Differences in survival rates were not substantial between oak and intolerant hardwood species, but the difference was much more apparent between these species and intolerant hardwoods (Figure 2.4). Although the probability of survival was significant between trees with stem form A and B, the average probability of survival for form B was only slightly lower (Figure 2.4).

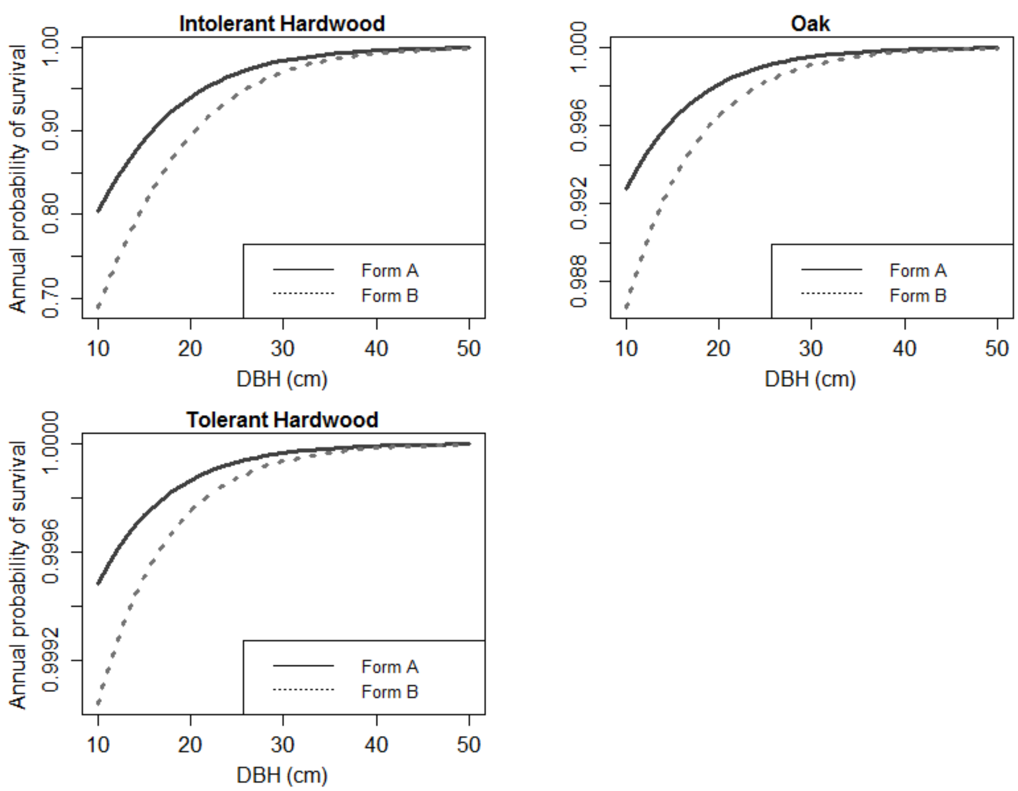


Figure 2.4. Annualized survival predictions across species and form classes. Predicted probabilities of tree survival shown for intolerant hardwoods (top left), northern red oak (top right), and tolerant hardwoods (bottom left) by form class over diameter at breast height (DBH; cm). Form class A is trees of ideal form (NHRI form class F1), while form class B is tree of poor form (NHRI form classes F2-F8). Note differences in the scale of the y-axis.

Table 2.7. Parameter estimates and fit statistics for DIR, PAI and survival models. Parameters a, b, c correspond to diameter increment bias model (Model 1), PAI model (Model 2), and survival model (Model 3) respectively.

Model	Parameter	Variable	Est	SE	Pr
Equation 1	a_0	Intercept	-0.0411	0.1463	0.7789
	a_1	OH	0.3500	0.0470	<0.01
	a_2	LR	-0.0836	0.0465	0.0725
Equation 2	b_0	Intercept	0.9264	0.1577	<0.01
	b_1	log (DBH)	0.0376	0.0354	0.2883
	b_2	BAL	-0.0034	0.0006	<0.01
	b_3	CSI	-0.0359	0.0072	<0.01
	b_{41}	Oak	-0.0572	0.1343	0.6705
	b_{42}	Tolerant HW	-0.1638	0.1133	0.1484
	b_{51}	Form B	-0.0335	0.1131	<0.01
	b_{61}	LR	0.0455	0.1132	<0.01
	b_{71}	DBH x Oak	0.0524	0.0432	0.216
	b_{72}	DBH x Tolerant HW	0.0577	0.0381	0.1296
Equation 3	c_0	Intercept	1.0297	0.9723	0.2897
	c_1	DBH	0.1341	0.0141	<0.01
	c_2	BAL	-0.0546	0.0119	<0.01
	c_{31}	Oak	3.5108	0.3005	<0.01
	c_{32}	Tolerant HW	6.1533	0.3795	<0.01
	c_{41}	Form B	-0.6145	0.1265	<0.01
Fit Statistics	R2 - M	R2 - M	RMSE	R2 - M	AUC
Equation 1	0.05	0.32	1.90	-0.50	-
Equation 2	0.16	0.24	0.26	-0.04	-
Equation 3	-	-	-	-	0.82

Discussion

Results from the assessment of the regional diameter increment equation suggested that the model over-predicted annualized diameter increment across certain species and risk classes. No systematic trends were detected in bias for the variables accounting for tree size, competition and site suggesting that the current regional model does a reasonable job of accounting for these factors. The lack of bias across these variables makes sense as this model was fit using an extensive database collected across the Acadian Region, which covers a wide range of diameter classes and stand conditions. Out of the species examined, the model tended to over-predict aspen, birch, and maple (OH, Figure 2.1) the most. The average ratio of predicted to observed diameter increment for northern red oak was significantly lower (Oak, Figure 2.1). One of the possible reasons for the discrepancy between the two species groups maybe due to the site conditions where the species occurred. A large portion of the maple, aspen, and birch observations was obtained from the PEF and SFMA, both of which have lower site quality than the HRF and Kingman Farms Research Forest. It is possible that the regional model was developed using higher quality sites for maple, birch, and aspen while site conditions for red oak were similar to that of HRF and Kingman Farms. The effect of risk class on diameter increment tended to be over predicted by the regional equation, although the difference between parameter estimates for high and low risk trees was only marginally significant ($p = 0.08$). Currently the regional diameter increment model only uses crown ratio to account for tree vigor. The tendency of the equation to over-predict increment of high-risk trees could suggest that the inclusion of risk classifications could help account for variation in diameter growth attributed to tree health that crown ratio does not explain.

The model used to quantify PAI consisted of DBH, BAL, species, form, risk and CSI as explanatory variables (Table 2.7, Equation 2). While DBH was as significant variable it did not demonstrate the unimodal-peaking behavior that has been observed in numerous studies that have focused on developing diameter increment models using more extensive datasets (Uzoh et al. 2008; Adame et al. 2008; Haung and Titus 1995). Instead diameter increment consistently increased across the range of diameters observed in the dataset. This was an unexpected result but there could be a couple potential reasons why this trend was observed. First, a large portion of trees were sampled in the PEF and SFMA across a wide range of sites undergoing a large array of silvicultural treatments. Depending on the timing of these treatments (number of years since they occurred), middle-to-larger DBH ranges may be experiencing higher diameter growth rates compared to trees of corresponding size in untreated stands. Second, with the exception of northern red oak, a large proportion of diameter measurements were taken on trees with smaller DBHs (10 -30 cm) and consequently the decline in increment across tree size was not detected due to limited observations in upper diameter ranges (> 30 cm). While the trend in diameter is not consistent with that found in most other studies, it does agree with work of Lhotka et al. (2010), who did not observe the peaking behavior in diameter for oak and pine species in mixed-wood stands in the Ozark Region.

Diameter growth was found to be inversely related to one-sided competition. Specifically, growth was not found to be significantly limited to two-sided competition and was instead explained solely by BAL. Metrics of two-sided competition did display negative parameter estimates in the model development process but did not achieve high enough significance to warrant inclusion in the final model ($p < 0.05$). The importance of BAL or modifications of it has been frequently recognized in diameter increment models (e.g. Lhokta et al. 2010; Adame et al. 2008; Uzoh et al. 2008) and likely suggest that social position had more influence in limiting diameter growth than overall competition for site resources.

The parameter estimate for CSI was negative indicating that sites considered to have higher productivity demonstrated lower PAI. This trend was surprising but the negative parameter estimate could be influenced by the level of management activity across the different sampling locations. Among the four sites investigated in this study, the PEF and SFMA had the lowest average CSI values compared to the HRF and Kingman Farms Research Forest (data not shown). While it would be expected that these locations would have lower PAI, both of these sites are actively managed in contrast to HRF and Kingman Farms Research Area. Consequently, the effect of CSI could be confounded by current and past silvicultural treatments on both these sites. In addition, a potentially larger range of sites would likely be needed to account for the broad range of CSI values in the region.

Form was a significant variable in predicting diameter increment, however, its effect was not substantial (Table 2.7, Equation 2). Specifically trees that displayed single straight stems (F1), low forks (F7), or multiple stems (F5, F8) had higher average diameter growth rates than trees that had multiple sweeps or displayed significant lean. Very little work has focused on relating different stem form to diameter growth but the trend of trees with multiple stems (F5, F8) having larger growth rates agrees with Hann and Hanus (2002). In addition, slower growth rates observed by trees with significant lean (F6) displaying excessive lean demonstrated a reduction in diameter growth, which corresponds to the trend of observed lower diameter increment for trees with significant lean (F6), and also agrees with findings from Hann and Hannus 2002. Higher growth rates for trees with forks on the lower portion of their stem (F7) could correspond to trees with larger live crowns with higher leaf areas and photosynthetic capacity (Monserud et al. 1995). In fact, the effect of crown size as expressed by crown ratio has been shown to have strong positive effect on diameter increment in several studies (Monserud and Sterba 1995; Weiskittel et al. 2007; Hann et al. 2003).

Trees considered to be high-risk (R3, R4) had lower diameter growth rates compared to low and moderate risk trees, although the difference was not substantial. These results align with work of Fortin et al. (2008) who observed that there was relatively small, but significant difference between high and low vigor trees for northern hardwood species in Quebec. While risk helped account for variation in periodic diameter increment, isolating the important factors that have the most limiting effect on growth using a binary classification system (LR, HR) is quite challenging. However, there are likely two factors that account for reductions in average diameter increment in high-risk trees (HR). First, risk classifications consider a trees a competitive status. Therefore, trees experiencing high competition in conjunction with an additional stem defect would have reduced diameter growth. Second, slower growth could be attributed to more severe defects such as cavities, decay, and fungal infections that have compromised the conductive tissue of a tree. Damage to components such as phloem and xylem could also reduce a trees ability to transport nutrients required for growth (Hann and Hanus 2002). Ultimately, further understanding of the defects contributed to lower growth rates was hindered by the unbalanced distribution of risk classes across species in this analysis (Table 2.3 and 2.4), particularly evident for high-risk and very high-risk trees. More extensive datasets are likely required to test if there is a gradient in terms of growth reduction across the NHRI risk classes.

The final model for annual tree survival was a function of DBH, BAL, species, and two classifications of form (A = F1, B = F2, F5, F6, F7 and F8). The parameter estimate for DBH was positive indicating that trees of larger size were more likely to survive. Several different transformations of DBH were added into the model framework to determine whether there was a decline in survival once trees achieved a large enough size indicating senescence induced mortality, but none were found to be significant. This result is not surprising as this pattern has typically been only observed for very large datasets with a wide range of diameters (Weiskittel et al. 2011; Adame et al. 2010). Survival had an inverse relation with BAL indicating that a trees competitive status played a significant role in determining whether a tree survived over the course of a growth period. Lower probability of trees surviving with larger BAL values most likely relates to trees that become suppressed and do not receive adequate sunlight or become more susceptible to forces such as windthrow, pests, and disease (Temesgen et al. 2005).

Overall, survival probability was much lower for intolerant hardwood species (aspen and paper birch) compared to oak and tolerant northern hardwood species (red maple, sugar maple, yellow birch, Figure 2.4). Higher probabilities of mortality for intolerant species have been demonstrated in several studies (e.g. Temesgen et al. 2005; Yao et al. 2001). The decline in survival rate for these species is hypothesized to be triggered by a decline in photosynthate which is required to meet these species respiration demand, particularly as competition of shade tolerant species increases (Temesgen et al. 2005). Indeed, many of the sites sampled in the study were dominated by shade tolerant hardwoods and softwoods that likely had a competitive advantage.

The probability of survival was significantly lower for all form classes (F2, F5, F6, F7, and F8) other than trees with single straight stems (F1) although the predicted difference was quite small. Among the trees that died and were not considered to have ideal form, the greatest proportion were those having multiple sweeps or were previously growing in a clump of multiple trees (Table 2.4). While the influence of stem form remains largely untested, there is some evidence from this analysis that trees associated with certain form classes may have elevated probability of mortality. For instance, it has been recognized that species growing in multiple stems as a result of stump sprout regeneration (Tubbs 1977; Smith 1997), may be potentially more susceptible to decay and consequently have a higher risk of mortality. Higher instances of mortality for trees with multiple stems could also be induced by competitive stress particularly for stems with lower DBH in the cluster (Adame et al. 2008).

Conclusion

In this study, quantitative models were developed to determine if stem form and risk had an influence on growth and mortality for several northern hardwood species. Assessment of bias in the regional diameter increment equation demonstrated that the equation tended to over predict for species and a binary classification of risk. Correction factors derived from the model only improved MB and RMSE for some species and risk class combinations. Development of a PAI and survival models indicated that both form and risk had a relatively small yet statistically significant effect. Based on the current results, a simplified version of the NHRI classification system would likely be more effective to characterize growth and mortality. However, the distribution of both form and risk was highly unbalanced across the species in the dataset and possibly understated the importance of some classifications.

Hardwood species will likely continue to play a significant role in the forest industry of the Northeastern United States and Canada due to their potential to yield valuable solid wood products. Management of these species is challenging since they have large potential to develop many types of undesirable defects, which can reduce their value. Based on the findings of this study, the NHRI classification system could help forest managers prioritize trees for harvest that could help balance the objectives of short term economic profit and long term retention of vigorous stands in selection cutting operations. Although the current NHRI system is somewhat challenging to implement due to the large number of form and risk classes a simplified version could allow for it to be integrated into large scale forest inventories that could provide a better characterization of the hardwood resource at the regional scale. Acquisition of larger datasets that characterize stem characteristics of hardwood species would allow for further refinement of quantitative tools that could provide better projections of the forest resource and should be a high priority for the region given the importance of hardwood species.

EPILOGUE

This study provided a quantitative analysis of the influence of stem form and damage on product potential, growth, and survival of several important northern hardwood species in the Acadian Forest region. This assessment was intended to achieve two primary goals: 1) refinement of the current version of the Acadian variant of the Forest Vegetation Simulator (FVS – ACD) and 2) assess the value of tree classification systems in the prediction and management of northern hardwood stands in the Northeast region. The outcomes of the modelling efforts in this study can be used to extend the capability of the FVS-ACD by allowing hardwood species to be assigned form and risk classifications in simulations and adjust predicted merchantable volume and diameter growth values based on these two attributes. In addition, the results also suggest that a simplified version of the Northern Hardwood Research Institute (NHRI) classification system could be used to enhance management and monitoring of hardwood species in the region.

In Chapter 1, potential sawlog recovery was assessed for red maple, northern red oak, sugar maple, and yellow birch using data collected in Maine, New Brunswick, and New Hampshire. Development of linear mixed effects models indicated that there were substantial differences in the proportion of sawlog volume in individual trees across NHRI form and risk classifications. As suggested in previous research, the implementation of a system with numerous classifications was unwarranted. Many of the stem form classifications were not observed frequently across the species and recoverable sawlog material could adequately be described using three classifications of stem form accounting for single straight stems, sweep or multiple stems, and low significant forks. In addition, a simple binary risk classification was appropriate for characterizing stem damage. Development of logistic regression models indicated that there were important differences in the occurrence of various stem forms and damage across species. None of the site-specific variables tested in the analysis were found to be influential in controlling either stem form or occurrence of damage in the hardwood species examined. However, based on previous work, there are likely factors such as stand development and harvest history which could potentially have important implications on development of stem form defects. Further work focused on identifying these factors is warranted.

Chapter 2 focused on determining the extent that stem form and risk influenced individual-tree diameter increment and survival. Using continuous inventory data from several sites in Maine and New Hampshire, the effects of form and risk on diameter growth were evaluated by examining bias in the regional diameter increment predictions used in FVS-ACD and through development of a periodic annual increment model. In general, the regional diameter increment equation tended to over predict observed short-term (<15 years) annualized increment for all species and two classes of risk accounting for stem damage severity. However, the magnitude in the over-prediction between the two risk classes was not large and only marginally significant. The developed PAI model suggested that both form and risk were significant variables although their effect size was relatively small. Trees having a single straight stem, multiple stems or low forks had overall higher diameter growth rates than trees with excessive sweep or lean. A binary classification of risk indicated that trees with extensive or severe wounds generally demonstrated slower growth rates than those with less severe or no wounds. A nonlinear logistic regression model was fit to assess annualized survival rate. Similar to the growth analysis, the results indicated that there was a statistically significant but relatively small differences in survival rates between a binary aggregation of NHRI stem form classifications. Specifically, trees with ideal form had on average a higher probability of survival compared to all other form classes in the NHRI classification system.

Examination of the results in both thesis chapters revealed several distinct patterns with respect to the influence that form and risk had on product potential, growth, and survival for hardwood species using the NHRI classification system. For all analyses, the use of eight stem form and four risk classes was unwarranted. For form, aggregations consisting of two to three classifications were sufficient to describe differences in sawlog volume, diameter growth, and survival rates. While the eight stem form classifications proved to be inefficient, most of the characteristics (sinuosity, multiple stems, and forks) defined in the NHRI protocol were important. For all analyses, with the exception of the survival model, risk was best characterized as two classes that distinguished trees with severe damage from those with little to no damage. Based on these findings a classification system consisting of four stem form classes that account for trees with single stems, sweep, multiple stems and low significant forks along with two classes of risk is recommended for management and monitoring of hardwood species in the northeast region.

Limitations

Although this study indicated that stem form and damage had implications on growth and yield applications for northern hardwood species, it did have several notable limitations. The datasets used in the analyses were highly unbalanced as there were large discrepancies across form, risk, and species, which became particularly evident in the growth and survival analyses. Deficits in both form and risk classes restricted inference in a couple ways. First, the unbalanced dataset did not allow for the effect of form and risk to be directly tested for individual species through development of species-specific equations or adequate testing of interaction terms between species, form and risk in the models that were developed. It is plausible that the effect of form and risk could vary considerably among species, particularly with respect to diameter growth and survival. Second, even when species were pooled together in analyses, the sample sizes of some form and risk categories were still relatively limited. While low sample sizes for these could suggest their inherent scarcity on the forest landscape, their overall effect on product recovery or tree development could not be adequately assessed.

The data in this study were sampled across a couple of sites that were undergoing different silvicultural treatments. The influence of these treatments was not accounted for in the analysis and potentially could have distorted the effect of form and risk in the growth and survival analysis. In addition, variables accounting for harvest history and stand level metrics such as density or species composition could not be integrated into the models used to predict the occurrence of stem form and risk since this information was not consistently available across Maine, New Hampshire, and New Brunswick. It is possible that these factors could have a substantial role in controlling development of certain stem form defects and damage.

Finally, even though this study indicated that a revised classification system could be used to discriminate between trees of varying stem quality and vigor it faces several shortcomings. First, although it is relatively straight forward which form attributes impact (sweep, multiple stems, forks) product potential, growth, and survival, the same is not true for risk. The binary risk classes proposed in the revised classification system encompass a wide range of defects which whose effects were not able to be individually tested given their relatively low occurrence. As a consequence, the risk classifications may be inefficient since they may not necessarily target the most influential defects in all scenarios. A second weakness of the current classifications, including the one proposed in this study, is that the influence of a defect may not be adequately reflected based merely on its presence or absence. Instead the effect of these defects on stem quality and vigor may be better expressed on a continuous basis. For example, while risk classes take into account the presence of an open wound or decay, they do not reflect its size. An estimation of wound size may provide more information with respect to recoverable product, growth, or probability of mortality rather than simply noting the defect’s presence. The same reasoning could also be applied to form characteristics, where information on the size or height of a fork for example would be more informative than a coarse determination of its relative position on the first 5m of the stem. However, inclusion of more detailed assessments of defects and form attributes may significantly increase the cost of stem quality and/or vigor assessment compared to the use of a tree classification system. Further work is warranted to determine if this additional information would be worth the added cost.

Management Implications

Forest managers are frequently faced with the challenging task of prioritizing trees to harvest in selection cutting systems. Failure to harvest the correct trees during cutting cycles can not only result in unproductive harvests, but also leave behind degraded stands of poor quality trees. Tree classification systems serve as tools to facilitate the decisions that tree markers must make prior to harvests. Unfortunately, many of the systems that are currently available are generally complex to implement, contain unnecessary classifications, or remain untested in terms of their efficacy.

The quantitative approaches used in this study suggest that a reduced version of the current NHRI classification system could be used to balance various objectives of selection cutting systems. The revised classification offers a simple framework consisting of four easily identifiable stem form characteristics and two classifications differentiating damage severity that can be quickly implemented in operational settings or forest inventories. In addition, the integration of both stem form and damage in a unified framework eliminates the need to use two separate classifications to assess stem quality and vigor. This proposed system has potential to address the different objectives that are encompassed in selection cutting systems. First, the system can be used to enhance the productivity of harvests by enumerating attributes that influence a trees product output and current monetary value. Second, stem form and risk can be used in conjunction to decide which trees should be retained as future growing stock. Finally, it is also likely that this system would be capable in scenarios where more emphasis is placed on ecological considerations. Trees characterized as having exceptionally poor form or demonstrate elevated risk could serve as refuges for wildlife or contribute to future coarse wood debris stocks.

The outcomes of the analyses used to validate the NHRI system can also be used to update the current version of FVS – ACD. Those managing forests in the Northeast rely on forest growth and yield models to project forest development and simulate outcomes of management regimes. Results from this study suggest that inclusion of form in risk classifications can enhance predictions of growth and mortality sub-models in FVS-ACD, especially if larger data sets including these classifications could be used for future model calibration. The increased accuracy of the model would allow for enhanced forecasting and monitoring of forest resources in the Northeast Region.

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BIOGRAPHY OF THE AUTHOR

Mark Castle was born on January 9, 1990 in Charlottesville Virginia. Mark grew up in the outskirts of Charlottesville in the small town of Ivy, Virginia. There he enjoyed running, hiking and recreating in the beautiful landscape that central Virginia had to offer.

In the spring of 2008 Mark graduated from Western Albemarle High School and entered James Madison University that fall. During his stay at Hames Madison University Mark studied geography, worked on a project involved with GIS forest fire modelling, and was fortunate enough to travel to southeast Alaska during his junior year. Mark graduated with his bachelors of science degree in geography in the Spring of 2012.

Upon completion of his undergraduate degree, Mark spent two years taking additional classes at Piedmont Virginia Community College, stocking produce at a local grocery store, and doing yard work for several people in Ivy, Virginia. In the summer of 2014 Mark moved to Orono, Maine and began his Master of Science degree in forest biometrics. Aside from working on his thesis, Mark enjoyed hiking along the coast and mountains of western Maine. Mark is a candidate for the Master of Science degree in Forest Resources from the University of Maine in August 2017.