COOPERATIVE FORESTRY RESEARCH UNIT
Research Proposal

PROJECT TITLE: Exploring the effects of thinning on stand- and tree-level mortality in Maine's spruce-fir forests

ABSTRACT:

The CFRU Commercial Thinning Research Network (CTRN) was established in 2001 to measure the effects of precommercial (PCT) and commercial thinning (CT) in balsam fir (*Abies balsemea*) and red spruce (*Picea rubens*) stands. Repeated observations over the last 9 years have created an extensive database. In this analysis, patterns of mortality at both the individual tree and stand-level will be assessed using multiple variable logistic regression. The effectiveness of different site (soil depth, drainage, etc.), stand (thinning intensity and type), and tree (size and social position) variables for estimating mortality will be assessed. Finally, a modifier for the current FVS-NE mortality model will be developed to account for expected bias in predictions for thinned and unthinned spruce-fir stands. Deliverables will include two technical papers on mortality patterns given PCT and CT at tree and stand levels, as well as a modifier for the FVS-NE mortality model. The modifier will be included in the development of the refined FVS growth and yield software system.

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PLANNED START DATE: October 2010
PLANNED TERMINATION DATE: September 2012

BACKGROUND

Pre-commercial (PCT) and commercial thinning (CT) have been the primary forest management tools used in Maine for the past few decades. For example, the Maine Forest Service (MFS) reported that 96% (447,977 acres) of the acres harvested in 2008 were considered partial harvests, which CT is a vital component. Furthermore, PCT increased 15% from 2007 and is expected to continue in the future (MFS 2009). In the latest timber supply outlook study by the MFS, 25% of the spruce-fir (*Picea rubens - Abies balsamea*) forests will be moving from seedling/sapling stages into merchantable sizes. This will result in substantial growth increases between 2010 and 2040 (MFS 1998). An in depth knowledge of silviculture in spruce-fir stands is now more important than ever for the effective, sustainable harvest and use of these maturing stands.

As a result of the 1998 MFS Timber Supply Outlook, the "Thinning in the Maine Forest Conference" in 1999, multiple meetings with cooperators and researchers, and a survey of CFRU cooperators prior to the 2000-2005 CFRU Program Prospectus, the Commercial Thinning Research Network (CTRN) proposal was written and accepted unanimously by the CFRU Advisory Committee. To date, only 6 year results have been formally presented to CFRU members using the CTRN data (Seymour 2008). This previous analysis was primarily focused on initial growth response among sites and treatments. Results showed the 33% low thinning removal on sites with no PCT were the only consistently effective treatment at the stand level. Seymour (2008) also found that early application of CT did not reduce yields compared to stands with no PCT, contrary to prior expectations. Overall, the trends found show a strong response to CT on sites with an application of PCT.

Mortality modeling specific to the northern Maine's forest types has little representation in the technical or scientific literature. Mortality in Maine's forest industry has been predicted primarily using the Forest Vegetation Simulator Northeast Variant (FVS–NE) growth and yield model, which covers a very broad region of northeastern United States. Based primarily on the CTRN data, Saunders *et al.* (2008) showed that FVS–NE is biased in its predictions of growth in Maine's spruce-fir forests, particularly when the stands have received either PCT and/or CT. Saunders *et al.* (2008) developed growth modifiers to improve FVS-NE predictions, but did not examine the accuracy of the mortality equations. Based on CTRN data, Seymour (2008) showed that the crown thinning - 50% removal treatment and both dominant thinning treatments resulted in the most volume loss due to mortality after 6 years. The low thinning – 33% removal was the only treatment to show significantly lower volume loss from mortality (Seymour 2008).

Important questions still remain about the influence of PCT and CT on stand- and tree-level mortality patterns. Some of the most relevant are: (1) how do mortality patterns change with thinning and time since treatment; (2) what are the primary causes of mortality and can they be predicted based on tree- and site-level information; and (3) how well do our current regional growth and yield models like FVS-NE represent mortality trends? The CTRN dataset continues to increase in size and relevance, which provides a unique opportunity to address these questions.

LITERATURE REVIEW

Influence of PCT and CT

PCT and CT are the primary silvicultural topics under discussion in the scientific literature (e.g. Moores et al. 2007). However, relatively few analyses have been conducted in and around the Acadian Region of Maine. One example of a long-term PCT study in Maine is found in Brissette *et. al.* (1999)who found that PCT resulted in greater growth and yield of selected crop trees compared to unthinned stands 18 year post treatment. The treatments included in their analysis were: (1) 1.5 m row thinning, no crop tree release in 0.9 m residual strips; (2) 1.5 m row thinning with crop tree release at 2.4 m in the strips; (3) spacing at 2.4m x 2.4m and (4) a control. In the PCT treatments, balsam fir and spruce crop trees were found to have nearly doubled in size (overall average growth of 8.4 cm) when compared to the control (overall average growth of 5.6 cm). This response was primarily attributed to the increase in average percent live crown of the crop trees, which was 46% percent higher than the control plots on average. .

A study by Weiskittel *et. al.* (2009) further confirmed the findings of Brissette *et. al.* (1999). Their study focused on stem dimensions, form, and branching characteristics of the PCT spruce-fir stand of Brissette *et. al.* (1999). Twenty-five years after treatment, it was found that the crop tree spacing of 2.4 m x 2.4 m significantly increased diameter, height growth, crown ratio, and crown width, while reducing height to diameter ratios. Stem taper significantly increased and lower bole branches were larger due to PCT, resulting in possible preclusion of crop trees from sawlog use. However, Weiskittel *et al.* (2009) concluded that gains in wood volume likely outweigh losses in log quality.

The findings of Weiskittel *et. al.* (2009) and Brissette *et. al.* (1999) correspond with the findings of Pitt and Lantaigne (2008) in a study on PCT in northwestern New Brunswick. Over a 42 – 44 year observation period, Pitt and Lantaigne (2008) found a 21% gain in merchantable volume in thinned stands over unthinned stands for spacings between 2.1 and 2.4 m. Stands thinned at 1.8 and 2.1 m showed the best balance between individual stem growth and effective density. As in Weiskittel *et. al.* (2009), spacings at 2.4 and 2.5 m resulted in increased taper and larger branch diameters, but increases in volume production provide the possibility for an earlier CT.

In a stand in Quebec, Pothier (2002) found no significant difference in balsam fir diameter growth due to PCT in a study of 20-year results. However, a spruce-budworm outbreak during the second 10 year period after PCT is hypothesized to be the cause lack of diameter growth. Indeed, Pothier (2002) described patterns of higher spruce budworm attack, e.g. higher mortality, on thinned stands compared to unthinned controls. However, Bauce (1996) found that thinning prior to an outbreak can decrease vulnerability of balsam fir to spruce budworm due to a quicker refoliation response.

Few of these previous analyses have assessed the effects of PCT and/or CT on stand- or tree-level mortality. Brissette *et. al.* (1999) did find that the fertilization, PCT, and their interaction accounted for 69% of the variability regarding crop tree survival, with PCT alone contributing to 68% of the variation. Although it is obvious that PCT and CT can significantly affect the stem dimensions, growth, and composition of spruce-fir stands, the influence of the treatments on mortality are relatively unknown. Studies on windthrow and breakage resistance of balsam fir dominated stands (Achim *et. al.* 2005, Achim 2005) discussed the effects of increased wind loads and increased taper on tree survival in PCT stands. Both studies found that proportionally greater gains in diameter than height were enough to offset higher wind loads from a thinned stand, resulting in the stand being less prone to windthrow and breakage than an unthinned stand. In a thesis on wind damage in Maine's forests, Perry (2006) reports that aspect, topography, and wind direction were related to stand mortality. Early spacing through PCT exposes trees to wind early enough for H/D ratios and root and cambial growth to increase wind firmness in preparation for CT. Otherwise, CT of unthinned stands results in stands unable to support themselves during typical wind occurrences.

Indeed, most studies on thinning in the Acadian region only include mortality assessment as a suggestion for future research (Weiskittel *et. al.* 2009, Pitt and Lantaigne 2008, Pothier 2002, Brissette *et. al.* 1999) Specific modeling of the multiple variables involved with PCT and CT and the corresponding residual stand dynamics in spruce-fir forests of Maine are needed to complete the understanding of such widely used silvicultural practices.

Modeling mortality

Methods for predicting mortality have varied (see Hawkes 2000). For empirical growth and yield models like FVS, a logistic regression equation is commonly used. The equations generally include measures of tree size, social position within the stand, and stand density. For example, in a study on Norway spruce (*Picea abies*), white fir (*Abies alba*), and other Austrian species, Monserud and Sterba (1999) defined the following model for individual tree mortality

$$P = (1 + e^{(b0+b1/D+b*2CR+b3*BAL+b4*D+b5*D\text{^}2)})^{-1}$$

where P is 5-year probability of mortality, D is diameter at breast height, CR is crown ratio, BAL is basal area in larger trees, and $b0$-$b5$ are estimated parameters. The study found that D^{-1} was highly significant and the most important factor for all species. Crown ratio was also highly significant for all species except oak (*Quercus* spp.). BAL was highly significant for all species except white fir and oak. Monserud and Sterba (1999) also found that the relative importance of crown ratio was higher for the shade tolerant species of their study (fir, spruce, and European beech (*Fagus sylvatica*).

In a study on Norway spruce, Scots pine (*Pinus sylvestris*) and other broad leaved species in Norway, Eid and Tuhus (2001) also had success in modeling individual tree mortality with a similar equation.The model, first proposed in Monserud (1976), was weighted by time to account for irregular re-measurement intervals. Eid and Tuhus (2001) also found D^{-1} and BAL to be highly significant factors in predicting mortality. The ratio of diameter over the basal area mean diameter (d/D_{BA}), a substitute for BAL, was found to be insignificant. Both Monserud and Sterba (1999) and Eid and Tuhus (2001) composed their prediction equations using national inventory data, comprising both even- and uneven-aged stands with varied forestry practices occurring amongst the sample plots.

In Scots pine plantations in northwest Spain, Dieguez-Aranda *et. al.* (2005) modeled stand level mortality with reference to stands either unthinned or lightly thinned from below. The study predicted mortality using a two step regression with the logistic equation as in Eid and Tuhus (2001) and Monserud and Sterba (1999). For predictions at the stand level, Dieguez-Aranda *et. al.* (2005) used basal area (*BA*), dominant height (*HD*, mean height of the 100 trees per hectare with the largest dbh), age (*A*), number of trees per hectare (*N*), site index (*S*), and relative spacing (*RS*). Relative spacing and basal area × stand age were found to be the best explanatory variables for the study area. Site index was indirectly included as age and height increase, which is consistent with results from Eid and Tuhus (2001).

The mortality model used in the FVS-NE uses relative height of a tree to the average height of the 40 largest diameter trees and a weighted value based species tolerance in the two equations below to predict mortality rate (Dixon *et. al.*1995).

$$MR = a_1 - a_2 * RELHT + a_3 * RELHT^3$$
$$MORT = MR * (1 - MWT) * 0.1$$

where *MR* is the proportion of the tree record attributed to mortality, *RELHT* is tree height divided by the average height of the 40 largest diameter trees, *MORT* is the final mortality rate, *MWT* is the mortality weight based on species tolerance and $a_1 - a_3$ are defined parameters (Dixon *et. al.* 1995). As previously mentioned, Saunders *et. al.* (2008) found FVS-NE biased in growth and yield predictions for PCT and CT stands and supplied modifiers for these models. However, Saunders *et. al.* (2008) only developed modifiers for the growth equations used in FVS-NE and did not assess the mortality equations. This raises questions about the validity of the FVS-NE mortality models and warrants further analysis.

PROJECT OBJECTIVES

The overall goal of this research project is to utilize the CTRN database to examine the influence of PCT and CT on mortality patterns in spruce-fir forest types in Maine. Specific objectives are:

1. Compare the influence of PCT and CT on stand-level mortality given variability between sites, timing of treatment, relative intensity of thinning, drainage, and site exposure.
2. Assess the influence of PCT and CT on individual tree mortality given tree characteristics (H/D, LCR, HT, DBH), social position, and surrounding competition using both distance– dependent and – independent variables. Breakage vs. windthrow of individual trees will be assessed relative to the different treatments.
3. Develop a modifier for an existing FVS-NE mortality model to account for the influence of PCT and CT.

RESEARCH QUESTIONS

Based on the literature review, the following research questions will be explored for each project objective:

Objective 1

1. Does altering the timing, relative intensity, or a timing/intensity combination of PCT and CT have a significant impact on stand-level mortality?
2. Does variability in drainage class, site exposure, or soil series have a significant impact on stand-level mortality after PCT and CT?

Objective 2

1. Does social position of an individual tree affect its survivability in PCT and CT stands when compared to unthinned ones?
2. Does surrounding competition affect the survivability of an individual tree?
3. Does tree height, DBH, H/D, and LCR influence the mortality rate of individual tree?

Objective 3

1. Is the predicted mortality rate in from FVS-NE for individual trees biased compared to observed mortality rates for PCT or CT?
2. Can a percent bias modifier be applied to the FVS-NE mortality model so mortality predictions match observed occurrences?

HYPOTHESIS

The objectives and research questions will provide the answers for the following hypotheses:

Objective 1

1. Higher intensity thinning will increase stand level mortality for spruce – fir stands due to increased wind exposure wind.
2. Higher intensity thinning on sites with higher water tables and a lower drainage class will increase mortality in spruce – fir stands.

Objective 2

1. Stands treated with dominant thinning will result in trees with less structural stability and increased individual tree mortality.
2. Low thinning will result in the least amount of mortality because residual trees will have lower H/D ratios.
3. Larger trees with smaller H/D ratios will see decreased rates of mortality.

Objective 3

1. FVS-NE will overpredict mortality and require a modifier to accurately predict individual tree mortality in stands receiving either PCT or CT for the Acadian Region.

EXPERIMENTAL DESIGN

The CTRN is composed of two main experiments. The first is considered the “No-PCT” experiment and was designed to explain the effect of CT and relative density reduction on mature spruce-fir stands. The second experiment, the "PCT" experiment, describes the effects of entry timing and relative density reduction on spruce-fir stands that have received PCT. Each experiment is described briefly below.

No-PCT

There are six commercial treatments and an untreated control being examined in the No-PCT study. A combination of thinning method (low, crown, dominant) and density reduction (33% and 50% of relative density) are organized in a 3x2 factorial design. An untreated control considered a self-thinning plot is also located on site. Low thinning was achieved by removing from the smallest diameter up to a reduction of the consequent density. Crown thinning was conducted by removing the upper crown competitors of crop trees based on a mean spacing to height ratio of 0.3. Dominant thinning was accomplished by removing trees from the largest diameter classes until the consequent density was reached.

PCT

Like the No-PCT study, the PCT treatments are also a 3x2 factorial combination comparing timing of entry (0, 5, and 10 years) and density reduction amount (33% and 50%). An untreated control was also established. Rankings were given to each plot based on initial relative density and used to establish timing of entry. This accounts for variation in initial plot conditions so treatments between densities did not result in plots of similar stand conditions.

Study area

The study sites for the CTRN consist of 12 sites located across diverse geographic regions around the state of Maine (Table 1). The site index values of the 12 sites range from 45.9 to 75.4 ft. Elevations for the sites are between 145 (C23) –and 2140 ft. (Rump Rd.). Within site elevation changes range from a 4 ft difference at the Harlow Rd. site to a 75 ft. change at the Alder Stream site. Site aspects range from N-NE facing at Schoolbus Rd. to W-SW facing at Harlow Rd. Aspect, elevation, and soil information for each site is listed in the table below. Most sites contain very deep soils with a mix of drainage classes between poorly drained to well drained. Table 3 in the Appendix describes each soil series by the USDA NRCS.

Measurements

There are three types of measurement schemes utilized in the CTRN. For the pre-treatment inventory measurements include DBH, azimuth, distance from center on every tree within a plot; total and crown heights on a subset of trees across DBH classes; and in-growth plots on PCT sites. The intensive measurement scheme records DBH, total height, crown height, and status for every tree, plus in-growth and dead or downed trees within each plot. The extensive measurement scheme records DBH and status on every tree plus in-growth and dead or downed trees. The timing for each measurement scheme is subject to the master entry schedule developed for the study.

Table 1. Various physiographic and soils attributes of the 12 CTRN sites in Maine.

		Elevation (ft)		Soil		
SITE	Aspect	Lower	Upper	Series	Depth to bedrock	Water drainage class
Alder Stream	SE	1180	1255	NA	-	-
Golden Rd.	S-SE	475	490	NA	-	-
Harlow Rd.	W-SW	506	510	MUB	Very deep	Well drained
Lake Macwahoc	S	550	565	TsC, Pa	Shallow, NA	Somewhat excessively drained, NA
Lazy Tom	NE	1400	1460	NA	-	-
PEF 23a	NE	145	160	HvB, HvG	Very deep	Moderately well drained
Ronco Cove	S-SW	1050	1065	NA	-	-
Rump Rd.	N	2100	2140	CPB	Very deep	Somewhat poorly drained
St. Aurelie	SE	1360	1385	MED	Very deep	Well drained
Schoolbus Rd.	N-NE	1710	1735	MTB	Very deep	Poorly drained
Sarah's Rd.	NW-SW	1560	1590	MKC	Very deep	Somewhat excessively drained, NA
Weeks Brook	W	820	830	MrB, DyB	Very deep	Poorly drained, moderately well drained

Initially, four status codes where used for an individual tree: (1) living, healthy; (2) living, ingrowth; (3) dead, unknown; and (4) living, broken top. Due to the ambiguity of the mortality code, a system of 14 status codes was implemented at the start of measurements in 2007. The 14 code system includes more detailed status codes regarding living tree health and cause of death. Using notes, new observations, and status through time, the current codes were retroactively applied to occurrences of mortality prior to the implementation of the codes.

ANALYTICAL APPROACH

Phase I – Data compilation and preliminary analysis.

Stand level analysis

Total occurrence of mortality at each site will be tallied and examined by measurement year. The timing of either PCT or CT and corresponding mortality occurrences will be examined and compared between sites. Occurrences of damage will be examined against time since treatment. These calculations will be tested between treatments and sites for significance and probability of occurrence. The PCT and CT treatments will be expressed both categorically as well as continuously. To express the treatments continuously, the proportion of basal area removed and the ratio of average diameter removed to residual diameter will be calculated from the pre- and post-inventory assessments. CFRU GIS layers will be combined with depth to water table layers and examined for variation between sites. In addition, annual climate information and soils information for each site will be obtained from PRISM and the USDA NRCS soil survey, respectively.

Tree level analysis

Observations of damage or other deleterious effects that correspond to a subsequent mortality occurrence will be examined. Social position and competition surrounding the subject trees will be examined with respect to mortality using both distance-dependent and distance-independent measures of competition. Distance-dependent measures to be considered are several size-distance indices and area potentially available. Distance-independent measures will include basal area in larger trees (BAL), crown competition factor in larger trees (CCFL), and relative tree size calculated as the ratio of diameter of subject tree basal area over mean diameter of plot.

Phase II – Revisit field sites

The CTRN database has a significant description on the aboveground influence of PCT and CT on spruce-fir stands. For a more complete analysis on mortality patterns, it is important to include some aspect of the belowground effects. Rooting depth, natural drainage classes, and soil textures can play an integral role in a tree's stability and survival.

The focus of the field work will be to collect data for within site variations of soil attributes. Soil series GIS layers will be used in conjunction with a CTRN site layer to determine the soil series present within plots at each site. Rooting depth, natural drainage, and soil texture will be assessed in three randomly located soil pits in each CTRN plot. Rooting depth to fine roots will be analyzed as a continuous variable. Natural drainage will be assessed using the 5 drainage site class scheme outlined in Briggs Site Classification Field Guide (1994), using soil color of horizons to predict drainage class. Soil texture will be recorded according to the Guidelines for Maine Certified Soil Scientists (2009). Depth of horizons will be recorded to the nearest cm. Finally, soil samples of available horizons will be collected and preserved for potential future studies on soil chemistry within the CTRN sites.

In order to maximize the benefits of this field work, some simple to collect information on wind exposure will also be recorded. Aspect and percent slope of each plot will be taken with a compass in the down-slope direction. Topographic exposure categories will be recorded as top, upper, mid, or lower slope, valley, and flat.

In addition to collecting valuable soils and topography information, damage severity codes will be developed and used to assess individual trees. Severity will be expressed as low, moderate, or high. On a random subsample of trees, crown vigor indices such as density, color, and transparency will be collected to potentially help in distinguishing future mortality patterns. Digital hemispherical photographs will aid in making these measurements.

Phase III – Final analysis and refit of FVS-NE mortality model

Stand level analysis

Multiple variable logistic regression equations will be used to determine the key variables affecting tree mortality amongst the treatments. The important variables that will be considered are thinning intensity, treatment (PCT or No-PCT), stand composition, density, rooting depth, natural drainage class, depth to water table, soil texture, site aspect, and exposure category. Treatments and sites will be considered fixed effects, while all other variables will be considered random effects. As such, the analysis will be treated as a mixed-effects model considering the nested and repeated nature of the experimental design. Two separate models predicting survival and percentage of defects as a function of treatment and time since treatment will be developed. The final model will attempt to relate stand mortality patterns to other site and treatment attributes.

Tree level analysis

Analysis at the tree level will be conducted in much the same way as at the stand level. Along with thinning intensity and treatment effects, tree size and social position will be tested. Social position will include analysis on crown class, BAL, and CCFL. Tree size will be tested as DBH and total tree height. Model development for individual tree survival will be regressed as a function of topographic exposure, social position, and thinning treatment.

Modifier for FVS

To predict mortality, FVS- NE uses a density related model that relies on the height of an individual tree relative to the average stand height. The CTRN data will be used to predict mortality using the FVS-NE equations. Bias from actual mortality rates will then be computed based on treatment. Finally, this estimated bias will be modeled as a function of treatment variables, creating a percent bias modifier for the FVS equations that will account for the intensity of the thinning treatment. This modifier will also be used in the development of the refined growth and yield software system.

ANTICIPATED BENEFITS

This project will utilize the CTRN data and contribute to the second objective identified in the 2006 – 2010 CFRU Prospectus. An in depth knowledge of tree mortality trends influenced by PCT will enable forest managers to better predict future yields of spruce-fir dominated stands. The result will be 2 technical reports on the important variables influenced by PCT and CT, and how they are related to mortality trends. In addition, the existing mortality model within FVS-NE will be modified to account for PCT, resulting in better projections of future yield in spruce-fir dominated stands.

SCHEDULE OF DELIVERABLES

This project will result in a better understanding of mortality prediction in balsam fir – red spruce dominated stands receiving PCT and CT. Important deliverables will include: (1) the addition of soil type, drainage class, rooting depth, and site exposure data to the CTRN database; (2) prediction models for mortality at stand and tree levels; and (3) a modifier for the existing FVS-NE mortality model to offset prediction bias.

Date	*Deliverable*
Aug 2011	Field season data added to CTRN database and readied for analysis
Dec. 2011	Report: Preliminary results of analysis
May 2012	Report: Final report on results
July 2012	Final presentation on results

COMMUNICATIONS PLAN:

Research results from this project will be communicated to the CFRU through oral progress presentations and a final project report. Data acquired will be added to the existing CFRU databank according to the required specifications. Two technical reports and peer-reviewed journal articles will be written based on the results of the project.

SUMMARY

Red spruce – balsam fir dominated stands are a major component of the commercial forest industry in the Acadian Region and with 25% of these forest types moving into commercially viable status between 2010 – 2040 (MFS 1998), it is important to have an understanding of expected stand dynamics. PCT and CT are heavily used management tools, but have limited documentation on their effects on spruce-fir stands in Maine. A few studies have found significant impacts of thinning of tree growth and stem dimensions, but most of these studies are specific to a single research location. In contrast, the CTRN provides data on thinning across a wide geographic range in Maine, coving sites of varying aspects, soil types, drainage classes, and climatic exposure. Thus, it is a unique opportunity to study the effects of PCT and CT on Maine's spruce-fir forests, which will provide an understanding applicable to a wide range of landowners.

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Appendix

Table A.1. Summary of literature related to PCT and CT in the Acadian Region.

Study	Location	Number of plots	Time since treatment	Scope	Key findings	Possible limitations
Achim *et. al.* 2005	Lauretian Mountains, Quebec	4	9 and 14 years	Individual tree	Increased diameter growth from spacing is directly proportional to wind resistance.	Not enough samples were broken to assess tree resistance to wind.
Brissette *et. al.* 2005	Penobscot Experimental Forest	32	18 years	Individual crop tree dynamics and stand level variation	Growth and yield was greater in uniformly spaced crop tree release strips than row thinning without crop tree release.	Individual tree crop trees were only measured so stand-level information is lacking; one site in Central Maine of moderate potential
Perry 2006	Northern Maine forests	36 active respondents	Varied	Stand level variation	Early PCT results in H/D ratios and root growth that adequately prepares for wind firmness following a future CT.	Data acquired through interviews and surveys, instead of direct observation.
Pitt and Lanteigne 2008	Northwest New Brunswick	48	42 – 44 years	Individual stem variation and stand level dynamics	Spacing at 2.1 and 2.4 m showed a 21% gain in mech. vol. over unthinned stands.	Relatively high site for the region; Dominated by balsam fir
Pothier 2002	Eastern Quebec	60	20 years	Individual stem and stand dynamics	PCT increases volume per hectare of large diameter trees.	A spruce budworm outbreak severely impacted most of the study sites.

Study	Location	Number of plots	Time since treatment	Scope	Key findings	Possible limitations
Weiskittel *et. al.* 2009	Penobscot Experimental Forest	9	25 years	Stem dim., form, volume, branch attributes of crop trees	PCT can have a significant impact on stem characteristics.	Treatments other than 2.4 x 2.4 m spacing were not considered.

Table A.2. Summary of literature related to mortality modeling.

Study	Location	Number of plots	Time since treatment	Scope	Key findings	Possible limitations
Diéguez-Aranda *et. al.* 2005	Galacia, Spain	68	7 years	Stand level mortality of Scots pine	A mortality model directly predicting tree reduction using all plots, regardless of mortality occurrence, is recommended.	Short time since treatment; conducted on a pine plantation
Eid and Tuhus 2001	Nation-wide grid across Norway	4506	Est. 1986 - 1993	Individual tree, even- and uneven-aged stand variation	DBH^{-1}, individual tree competition, site index, and the proportion of BA for species were significant explanatory variables.	-
Monserud and Sterba 1999	Nation-wide grid across Austria	22000	Est. 1981-1985	Individual tree mortality models for six species	DBH^{-1}, crown ratio, and BAL were the most important variables in a logistic prediction model.	-

Table A.3. USDA NRCS soil series and their key attributes.

					Horizon			
Series	**Abb.**	**Geographic setting**	**Drainage**	**Depth to bedrock**	**O**	**E**	**B**	**C**
Colonel	CPB	Glaciated uplands, 0-35%	Somewhat poorly drained	Very deep, Dense, loamy glacial till	0-1 in., dark red-brown decmpsd plant material	1-2 in., gradyish brown fine sandy loam	3-18 in., drk red brown to drk ylw brown, fine sandy loam	18-65 in., olive gravelly fine sandy loam
Dixmont	DyB	Till plains and ridges, 0 – 25%	Moderately well drained	Very deep, glacial till	0-2 in., v. dark grayish brown silt loam	None	2-26 in., brown – light olive brown silt loam	26-56 in., olive silt loam
Howland	HvB, HvG	Drumlins and till ridges, 0 – 25%	Moderately well drained	Very deep, glacial till	0-1 in., black sapric material	1-2 in., grayish brown silt loam	2-25 in., dk red brown – olive, silt loam – gravelly silt loam	25-65 in., olive gravelly silt loam
Marlow	MED	Level to very steep, 0-60%	Well drained	Very deep, mica schist, granite, and phyllite	0-3 in., v. dark gray fine sandy loam	3-6 in., gray fine sandy loam	6-31 in., ylwish red – olive, fine sandy loam	31-65in., olive gray fine sandy loam
Masardis	MKC	Deltas, outwash, eskers, kames, and terraces, 0-80%	Somewhat excessively drained	Very deep, glaciofluvial	0-2 in., black sapric material	2-3 in., grayish brown gvly fine sndy loam	3-19 in., dk-light brown-olive, gvly fine sandy loam	19-65in., olive-olive gray xtrmly course sand
Monarda	MrB, MTB, MUB	Lower slopes, 0-15%	Poorly drained	Very deep, glacial till	0-3 in., mucky peat	3-6 in., light grey silt loam	6-20 in., light olive/olive silt loam	20-65 in., olive gravelly silt loam
Peat and muck	Pa	-	-	-	-	-	-	-
Thorndike	TsC	Hills and mountains, 0-45%	Somewhat excessively drained	Shallow, glacial till	0-3 in., black sapric material	3-4 in., pink-gray channery silt loam	4-18 in., ylw red to drk ylw brown, channery silt loam	

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