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THE GROWTH, YIELD, AND FINANCIAL PERFORMANCE OF ISOLATED EASTERN WHITE PINE (PINUS STROBUS L.) RESERVE TREES

By

Christopher E. Zellers

B.S. The Richard Stockton College of New Jersey, 2007

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(in Forest Resources)

The Graduate School

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August 2010

Advisory Committee:

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By Christopher E. Zellers

Thesis Advisor: Dr. Robert S. Seymour

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements for the
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The ability of eastern white pine (*Pinus strobus* L.) to persist as emergent trees makes this species well suited to silvicultural systems in which they are retained as isolated reserves after a regeneration harvest. While such systems are implemented throughout the Acadian spruce-fir region of Maine, little is known about the growth response and financial performance of eastern white pine following complete release from competition. In this study, 77 trees from 8 sites throughout the Acadian spruce-fir region were sampled tree and crown measurements, and increment cores were extracted at breast height, as well as from the top of the valuable first 16 foot log. Volume growth was examined prior to and following release, and overall response to release was favorable. A subsample of 9 trees climbed to measure basal diameter and vertical location of each branch to develop allometric leaf area equations and to examine influence of site productivity and age on growth efficiency. Leaf area-volume increment relationships were modeled with a nonlinear power function with a random effect for site, and employed to forecast future growth. A sawmill simulator was used to estimate post-release standing tree values and financial analysis was performed to assess performance of completely released trees for an unpruned and a hypothetical pruned scenario. Unpruned trees, on average exhibited peak net present value 52 years post-release.

Pruned trees declined in net present value following release, due to high initial values. The net benefit of pruning reached its maximum 30 years after pruning, and stayed positive for 101 years, suggesting that pruning is a viable practice for eastern white pine that will be released and retained as reserve trees. The retention of eastern white pine reserve trees appears to be both biologically and financially sound, but forest managers should be careful to select vigorous younger trees as reserves to maximize financial performance.

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CHAPTER ONE

LEAF AREA AND GROWTH EFFICIENCY OF ARCHETYPAL EASTERN WHITE PINE TREES GROWN IN ISOLATION

ABSTRACT

The ability of eastern white pine (*Pinus strobus* L.) to persist as emergent trees makes this species well-suited to retention as reserve trees in the mixed coniferous forests in the Acadian region of Maine. While there are many two-aged stands with pine reserves across the region, the growth and quality of these trees has never been studied. To assess the viability of such a silvicultural system, we selected 77 reserve trees from 8 forest stands throughout the spruce-fir region of Maine. Each tree was assessed for stem quality, and increment core data were used to reconstruct growth response to release. Allometric leaf area relationships were established using the branch summation method, and growth efficiency was assessed. With the exception of one site, trees responded well to complete release, with mean annual volume increment increasing 17.0 (± 2.2) $dm^3 \cdot yr^{-1}$ post-release. On average, growth efficiency was 0.22 (±0.01) $dm^3 \cdot m^2$, and projected leaf area was 349.4 (±20.0) m^2. Mean current annual volume increment was 63.3 (±3.2) $dm^3 \cdot yr^{-1}$. Silvicultural systems with extended rotations for isolated reserve white pines is biologically feasible, however the many details must be addressed by financial analysis using equations developed in this study.

INTRODUCTION

The financial performance of eastern white pine depends largely on how it is managed. Silvicultural systems that result in large diameter trees that yield knot-free lumber can maximize financial returns, yet often involve significant investments in precommercial thinning and pruning operations, especially when grown in pure, even-aged stands. Historically, most white pine research has focused on old-field monocultures, which were at one time abundant throughout New England. As time has passed, this resource has dwindled, and so has much of the research on this species.

Research has shown that white pine can display the good stem form required to yield high value lumber when grown in mixed, stratified stands in combination with more shade tolerant conifers, such as spruce, fir and hemlock (Fajvan and Seymour 1993). The other species allow for high density, resulting in straight boles, without the high risk of white pine weevil (*Pissodes strobi* [Peck]) attacks associated with monocultures. This approach has other distinct benefits, due largely to the growth characteristics of white pine. Because white pine continues to grow well longer than red spruce and balsam fir, a few high quality pines can be retained through a second rotation, so as to develop into large diameter crop trees. This is possible because white pine responds well to heavy release and remains relatively windfirm, even as isolated individuals (Bevilacqua et al. 2005). The second rotation of spruce and fir also promotes natural branch shedding, which may reduce the need for pruning operations.

While it is certain that knot-free sawlogs offer a much higher financial return than lower grades of white pine, it remains unclear as to when white pine reaches financial maturity.

Determination of financial maturity is dependent on several variables, including changing growth rates, costs and returns of silvicultural investments, and guiding rate of return. With eastern white pine, grade yield must also be considered, because of the premium placed on the highest grades of lumber. Much of the research to this effect (Chappelle 1966, Hibbs and Bentley 1987) is no longer relevant due to changes in market conditions for white pine lumber. Development of financial maturity guidelines that are relevant to landowners in Maine would be especially helpful, as white pine has arguably become the most important commercial species in the state. Of the estimated 142 million live white pine trees growing on timberland in the state, nearly 16% are in diameter classes of 15" or greater at breast height (McWilliams et al. 2005), so it stands to reason that older estimates of financial maturity are no longer valid.

To develop a viable financial maturity model, a further understanding of white pine growth, especially in larger trees, is needed. Recent research has shown that white pine grown in monocultures at unconventionally low densities can maximize tree level growth, with little sacrifice in stand level growth (Seymour 2007). Isolated white pines grown in irregular, mixed-species stands likely would also exhibit such patterns, but it is unknown what effects such a system would have on lumber quality. It has been suggested that white pine may exhibit ring shake as a result of growing in isolation, although this has previously been shown to be found primarily in slow growing trees with small crowns and little taper (Page and Smith 1994), which would not be characteristic of a heavily released crop tree.

The purpose of this study was to examine the growth response of completely released mature eastern white pine trees, as well as assess stem quality of trees grown in isolation.

Specific objectives were to quantify volume increments (VINC), model relationships between tree characteristics and projected leaf area (PLA), and model relationships between PLA and VINC. These findings provide the basis for a companion study that forecasts growth of isolated crop trees, and better assess the financial viability of retaining trees for extended periods of time.

METHODS

Study sites

Eight forest stands throughout the spruce-fir region of Maine, USA were selected for this study (Table 1.1). Each stand was two-aged, with a mixed conifer regeneration stratum developing under a sparse canopy of heavily released eastern white pine trees grown in relative isolation. The harvests that created this structure occurred between 1980 and 1994 and removed most or all of the mature spruce and fir. Soils ranged from somewhat poorly-drained to very poorly-drained (Briggs 1994).

Table 1.1. Study stand locations, harvest years, soil drainage class (Briggs, 1994), sample size, and sample size of climbed trees.

Site	Location	Harvest Year	Soil Drainage Class	Sample Size	Climbed Sample Size
Dead River Twp.	N 45° 12’, W 70° 16’	1984	3 – Somewhat Poorly Drained	9	1
Long Pond Twp.	N 45° 36’, W 70° 02’	1989	4 – Poorly Drained	9	0
Penobscot Experimental Forest, Compartment 2	N 44° 52’, W 68° 39’	1984	3 – Somewhat Poorly Drained	20	2
Topsfield Twp.	N 45° 28’, W 67° 51’	1992	4 – Poorly Drained	7	1
T3 R12	N 45° 56’, W 69° 15’	1987	4 – Poorly Drained	10	2
T4 R12	N 45° 58’, W 69° 11’	1991	3 – Somewhat Poorly Drained	9	2
T5 R12	N 46° 06’, W 69° 15’	1994	5 – Very Poorly Drained	4	0
T39 MD	N 45° 01’, W 68° 18’	1980	--	9	0

Table 1.2. Summary statistics for all trees included in this study. Attributes include diameter at breast height (DBH), total height (HT), crown length (CL), crown projection area (CPA), stem class form (GFC), and branch diameters (BD).

Site	DBH (cm)	HT (m)	CL (m)	CPA (m^2)	GFC	BD (cm)
Dead River Twp.						
Mean	54.2	21.8	16.3	221.7	77.6	2.0
Standard Error	2.8	0.6	0.8	19.2	0.7	0.1
Minimum	40.0	18.6	12.9	135.5	73.4	0.1
Maximum	70.1	25.8	20.2	324.7	80.4	12.6
Long Pond Twp.						
Mean	42.5	21.4	13.4	172.3	78.0	--
Standard Error	1.3	0.4	0.4	18.2	1.0	--
Minimum	36.8	19.7	10.9	101.2	72.3	--
Maximum	48.3	23.1	15.2	283.5	82.3	--
Penobscot Experimental Forest, Compartment 2						
Mean	55.8	25.6	15.8	345.4	81.1	3.3
Standard Error	1.2	0.3	0.5	16.77	0.5	0.2
Minimum	45.3	22.9	11.2	160.9	75.3	0.1
Maximum	70.6	30.3	22.7	546.1	87.5	17.3
Topsfield Twp.						
Mean	52.6	24.1	14.4	275.6	77.0	6.8
Standard Error	2.8	0.7	0.6	26.73	3.2	0.5
Minimum	39.6	20.7	11.4	140.3	49.1	0.2
Maximum	63.6	27.1	16.4	387.0	83.1	12.9
T3 R12						
Mean	48.4	22.9	14.0	273.0	78.9	3.6
Standard Error	2.8	0.6	0.7	27.3	0.8	0.2
Minimum	34.4	19.5	11.2	144.9	75.4	0.1
Maximum	63.9	25.6	18.4	410.5	82.3	13.6
T4 R12						
Mean	42.5	21.3	11.7	203.0	78.1	2.3
Standard Error	1.7	0.9	0.7	16.2	1.0	0.1
Minimum	34.6	17.6	8.2	127.6	71.2	0.2
Maximum	53.1	26.7	16.9	304.9	82.2	9.9
T5 R12						
Mean	48.3	21.9	11.2	218.3	80.4	--
Standard Error	12.2	2.8	2.5	46.8	0.9	--
Minimum	33.3	17.9	8.2	141.0	78.8	--
Maximum	96.7	33.1	21.0	402.3	83.4	--
T39 MD						
Mean	60.6	26.0	13.2	351.1	79.3	--
Standard Error	5.0	0.8	1.0	37.9	1.2	--
Minimum	42.8	21.2	9.6	166.6	72.1	--
Maximum	99.7	30.7	20.8	497.0	83.3	--

Data collection

Fixed radius plots (0.1ha) were established to survey the reserve overstory. Each reserve tree was measured for diameter at breast height (DBH, 1.37m) and crop tree suitability (having straight lower boles free of obvious defect and crowns not engaged with neighboring trees). Suitable trees were stratified into 10 cm diameter classes, and a proportional subset (n=77) was selected at random. Each tree in the subset was measured for total height, height to base of live crown, defined as the lowest contiguous live whorl, crown radii in six directions, diameter at 5.18m, and bark thickness in two locations at both 1.37m and 5.18m. Two increment cores were extracted at 1.37m, and one at 5.18m. Increment cores were scanned at 1200 dpi and measured with the WinDendro® software package (Regent Systems, Inc. 1992).

A subset of the sampled trees (n=9) was then selected to represent the range of DBHs at the time of release, as determined through increment core data. The subject trees were climbed, and all live branches were measured for basal diameter and height. Epicormic branches were also measured and noted. The branch summation method (Monserud and Marshall 1999) was employed to estimate projected leaf area (PLA). For this process, three branches were removed for detailed analysis; one from the base of the live crown (BLC), one from the sixth highest whorl, and one from the whorl median to the BLC and the sixth highest whorl. The sample branches were chosen by taking the branch nearest a randomly selected azimuth direction. Needle samples from each sample branch, consisting of approximately 100 needles, were collected and frozen in the field to reduce moisture loss. The frozen needles were then thawed, and scanned at 1200 dpi, and the PLA was measured to the nearest 0.0001 cm^2 using the WinSeedle® software package

(Regent Systems, Inc. 1992). These needles were then oven dried at 65° C for 72 hours and weighed to the nearest 0.0001 gram to determine specific leaf area (SLA; $cm^2 \cdot g^{-1}$). The remainder of the foliage from the three sample branches from each tree was then oven-dried for two days, at which point needles were separated from any non-photosynthetic tissue. Needles were then re-dried separately prior to obtaining their masses.

Table 1.3. Mean volume estimates for study trees by site. Standard errors in parentheses. Whole tree cubic feet estimates derived from Honer (1967). Board foot estimates derived from Leak, et al (1970).

Site	Tree Vol. (dm^3)	Tree Vol. (bd ft)	Butt Log Vol. (bd ft)	Top Log Vol. (bd ft)	Vol. in Butt Log (%)
Penobscot Experimental Forest, C2	2565.5 (135.9)	610.8 (34.5)	220.2 (10.0)	390.6 (24.8)	36.70 (0.01)
T39 MD	3222.5 (699.4)	779.0 (179.7)	262.2 (47.8)	516.8 (122.5)	35.86 (0.02)
Topsfield	2118.1 (269.0)	495.3 (69.0)	190.4 (18.9)	304.9 (50.3)	42.2 (0.0)
Long Pond	1197.8 (65.1)	259.0 (16.3)	115.2 (7.2)	143.8 (9.7)	44.6 (0.0)
T4 R12	1237.4 (150.1)	269.7 (38.4)	117.3 (10.5)	152.4 (28.2)	46.0 (0.0)
T5 R12	2528.7 (1696.2)	600.8 (435.3)	196.5 (110.5)	404.3 (324.9)	48.0 (0.1)
T3 R12	1733.0 (215.2)	396.4 (55.2)	154.5 (17.4)	241.8 (37.9)	40.6 (0.0)
Dead River	2106.8 (254.9)	492.3 (35.2)	200.7 (21.8)	291.5 (44.2)	42.1 (0.0)
Summit	3010.1 (430.4)	724.5 (110.6)	232.8 (28.9)	491.7 (83.3)	32.8 (0.0)

Table 1.4. Summary statistics for all trees included in this study. Attributes include projected leaf area (PLA), growth efficiency (GE), and tree age.

Site	PLA (m^2)	GE (dm^3 m^{-2})	Age (years)
Dead River Twp.			
Mean	378.1	0.31	72.1
Standard Error	51.4	0.02	1.1
Minimum	159.5	0.20	68
Maximum	653.3	0.43	77
Long Pond Twp.			
Mean	204.9	0.20	112.8
Standard Error	19.1	0.02	3.1
Minimum	121.1	0.12	97
Maximum	305.5	0.29	127
Penobscot Experimental Forest, Compartment 2			
Mean	463.2	0.16	108.0
Standard Error	35.2	0.01	1.8
Minimum	219.8	0.09	93
Maximum	790.5	0.22	128
Topsfield Twp.			
Mean	399.5	0.18	131.6
Standard Error	59.6	0.01	1.5
Minimum	169.1	0.12	128
Maximum	579.1	0.24	139
T3 R12			
Mean	319.7	0.27	79.2
Standard Error	47.4	0.02	1.4
Minimum	118.8	0.20	74
Maximum	625.0	0.44	87
T4 R12			
Mean	202.3	0.27	83.2
Standard Error	19.6	0.01	2.9
Minimum	123.8	0.22	66
Maximum	318.5	0.33	98
T5 R12			
Mean	142.2	0.29	80.3
Standard Error	15.5	0.03	4.0
Minimum	111.4	0.23	74
Maximum	171.6	0.36	91
T39 MD			
Mean	479.4	0.15	144.6
Standard Error	69.9	0.01	15.3
Minimum	197.4	0.11	99
Maximum	768.4	0.21	245

Analysis

Branch level projected leaf area (BLA) from the 27 sample branches from the climbed trees were used to fit a predictive model. The model formulation is as follows:

[1]

$$e^{BLA} = \beta_0 + \beta_1 * e^{BD}$$

where BD is the branch basal diameter (mm). BLA was then back-transformed, using a log-bias correction factor of 1.15 (Sprugel 1983). Relative depth in crown was explored as a covariate, but was not significant.

Table 1.5. Branch leaf area equation [eqn 1] parameter estimates and fit statistics. SE - standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	p Value	RMSE	R^2
β_0	-5.8948	0.4501	< 0.0001	0.5127	0.9050
β_1	1.8514	0.1174	< 0.0001		

Tree level projected leaf area (PLA) was estimated for the nine climbed trees by summing the predicted BLAs, and then used to fit the following model:

[2]

$$PLA = \beta_0 * DBH^{\beta 1} * CPA^{\beta 2}$$

where DBH is diameter at breast height (1.37m) and CPA is crown projection area. Several other model forms were also evaluated (Table 1.2), however, this formulation provided the best, and most unbiased prediction, as assessed using root mean squared error and residuals. This allowed PLA prediction for all of the study trees. Both models were fit using generalized nonlinear least squares in the nlme library (Pinheiro et al. 2008) in R (R Development Core Team 2008).

Table 1.6. Model formulations and fit statistics for estimating tree-level projected leaf area (PLA). Independent variables include sapwood basal area (SBA, cm^2), live crown length (CL, m), diameter at breast height (DBH, cm), total stem height (HT, m), modified live crown ratio (mLCR), and crown projection area (CPA, m^2). AIC – Akaike's information criteria; BIC – Bayesian information criteria; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Model	Equation	AIC	BIC	RMSE	R^2
SACL	$PLA = \beta_0 * SBA^{\beta_1} * CL^{\beta_2}$	110.76	111.55	72.97	0.77
CLDH	$PLA = \beta_0 * CL^{\beta_1} * e^{(\beta_2 * \frac{DBH}{HT})}$	110.53	111.32	72.04	0.78
mLCR	$PLA = \beta_0 * DBH^{\beta_1} * mLCR^{\beta_2}$	108.13	108.93	63.07	0.83
DCL	$PLA = \beta_0 * DBH^{\beta_1} * CL^{\beta_2}$	105.88	106.67	55.65	0.87
DCPA	$PLA = \beta_0 * DBH^{\beta_1} * CPA^{\beta_2}$	103.69	104.48	49.27	0.90

Table 1.7. Parameter estimates with standard errors and *p* values for selected models for estimating tree-level projected leaf area (PLA).

Model	β_0	β_1	β_2
SACL			
Estimate	0.1025	0.6910	1.089
Standard Error	0.2081	0.2940	0.4270
p Value	0.6398	0.0571	0.0435
CLDH			
Estimate	8.6833	1.5630	0.8845
Standard Error	9.9238	0.3779	0.2657
p Value	0.4152	0.0061	0.0158
mLCR			
Estimate	0.0596	2.2537	0.4662
Standard Error	0.1457	0.5577	0.7358
p Value	0.6968	0.0068	0.5497
DCL			
Estimate	0.0316	1.9960	0.5509
Standard Error	0.0538	0.5303	0.3795
p Value	0.5787	0.0094	0.1968
DCPA			
Estimate	0.0126	2.1025	0.3438
Standard Error	0.0186	0.4091	0.1680
p Value	0.5232	0.0021	0.0868

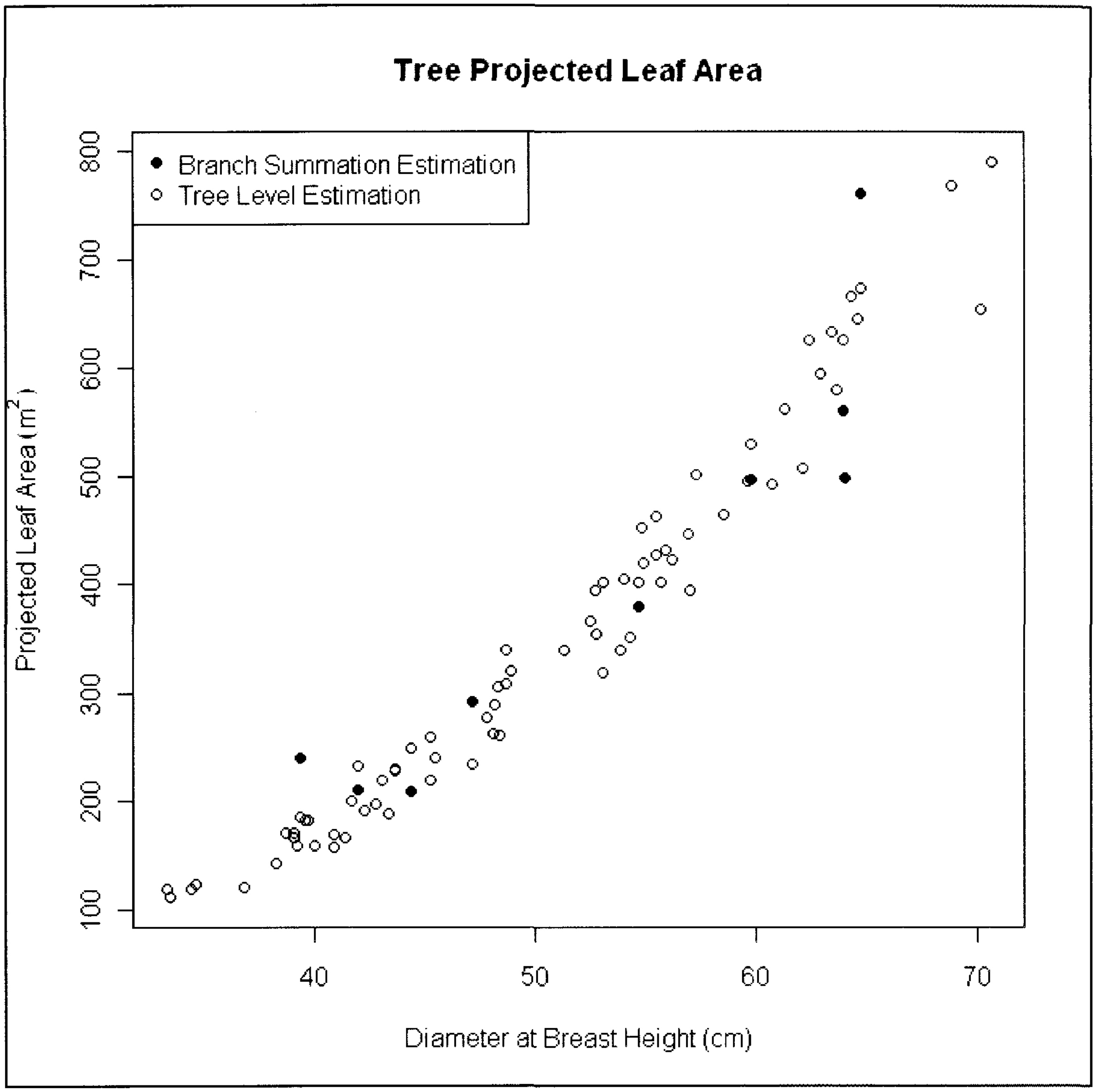

Figure 1.1. Projected leaf area (m^2) as a function of diameter at breast height (cm). Filled circles are climbed trees, and leaf area was estimated using the branch summation method. Open circles are leaf area estimates made using the whole-tree model.

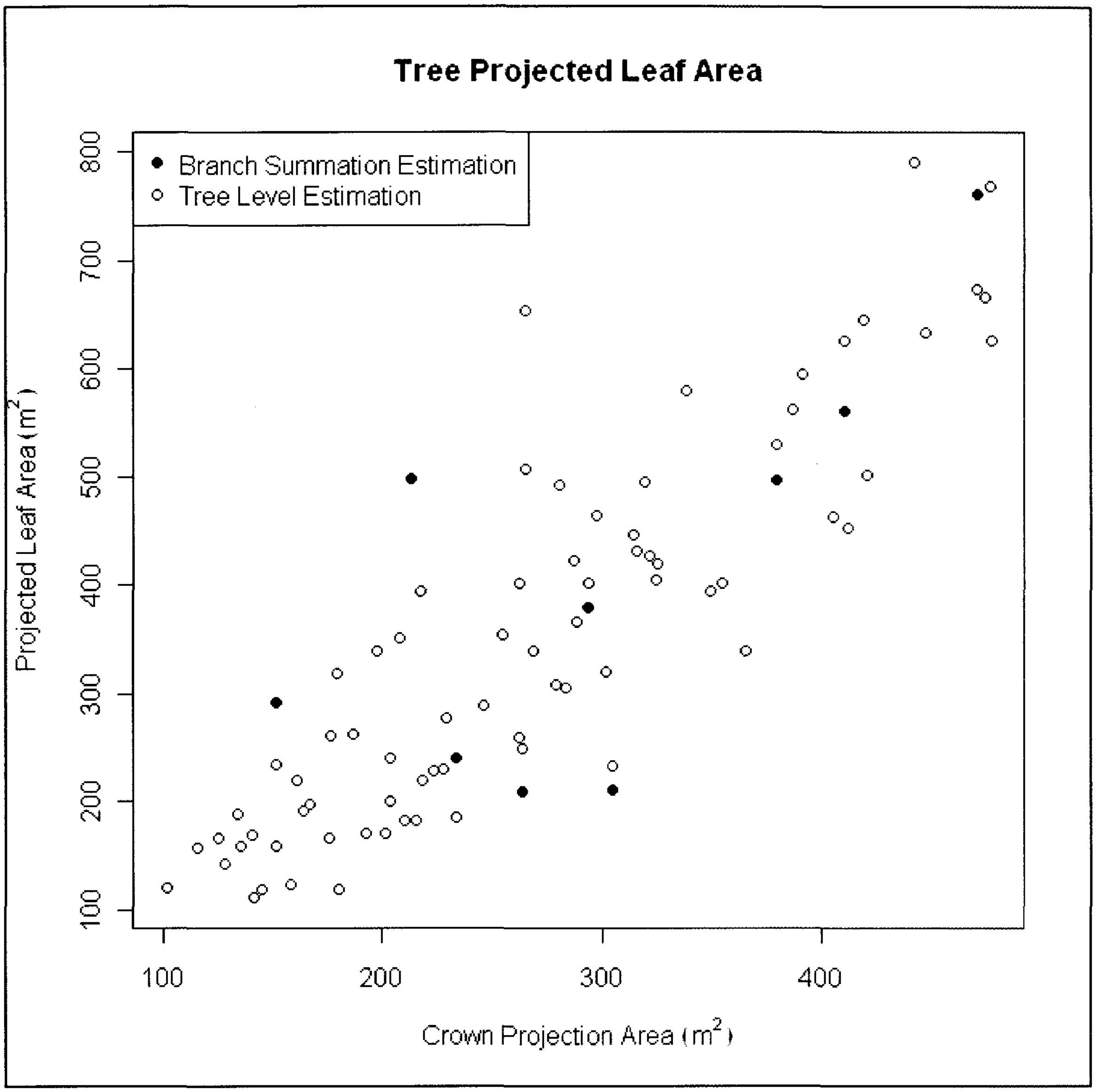

Figure 1.2. Projected leaf area (m^2) as a function of crown projection area (m^2). Filled circles are climbed trees, and leaf area was estimated using the branch summation method. Open circles are leaf area estimates made using the whole-tree model.

Annual volume increment (VINC) was estimated by reconstructing previous heights and diameters. Tree ring data were used to estimate tree diameters in 2003, five years prior to sampling. Site index was calculated for each tree (Carmean et al. 1989), which was then used to estimate heights in 2003. Honer's (1967) volume equation was then employed to estimate whole tree volumes in 2003, and the difference between 2008 volume and 2003 volume was divided by five to annualize volume increment. PLA was then used to predict VINC using a nonlinear mixed effects model taking the form:

[3]

$$VINC = \beta_0 PLA^{\beta_1 + b_1}$$

where b_1 is a random effect for site associated with the parameter β_1.

Table 1.8. Annual volume increment equation [eqn 3] parameter estimates and fit statistics. SE -standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	p Value	RMSE	R^2
β_0	1.1074	0.3713	0.0004	11.045	0.82
β_1	0.6978	0.0583	< 0.0001		

Table 1.9. Random effects for the annual volume increment equation [eqn 3].

Site	b_1
Dead River Twp.	0.0583
Long Pond Twp.	-0.0041
PEF, Comp. 2	-0.0286
Topsfield Twp.	-0.0041
T3 R12	0.0136
T4 R12	0.0091
T5 R12	0.0001
T39 MD	-0.0211

In an effort to elucidate the variation in VINC between sites, tree age was introduced as a covariate, as increasing age has been shown to have a deleterious effect on growth efficiency (Seymour and Kenefic 2002), or the stemwood growth per unit of leaf area (Waring et al. 1980). The following model was fit using generalized nonlinear least squares regression:

[4]

$$VINC = \beta_0 PLA^{\beta_1} AGE^{\beta_2}$$

where Age is tree age, in years. Parameter estimates and fit statistics can be found in table 1.10.

Table 1.10. Annual volume increment equation [eqn 4] parameter estimates and fit statistics. SE -standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	*p* Value	RMSE	R^2
β_0	26.5839	13.6205	0.0549	13.72	0.74
β_1	0.7522	0.0559	< 0.0001		
β_2	-0.7629	0.1049	< 0.0001		

RESULTS

Volume growth and stem form

The mean annual volume increment for all trees raised from 33.12 ± 1.98 dm^3 pre-release to 50.15 ± 2.68 dm^3 post-release, representing a 51.4% increase in mean annual volume increment, a significant increase ($P < 0.0001$) as determined by a pairwise t-test. All sites exhibited a substantial post-harvest increase in mean annual volume increment, with the exception of the Long Pond Twp. site (Figure 1.5). The trees at this site also had the smallest mean CPA (Table 1.2), which suggests that the larger pine trees had been removed in the harvest. Whole tree volumes across all sites ranged from 715.6 dm^3 to 10159.2 dm^3, with a mean volume of 2445.1 ± 149.1 dm^3 (Table 1.3). The mean percent of volume found in the butt log was 45.5 ± 0.01%.

Stem form of the trees was generally good (Table 1.2), with Girard form classes ranging from 49.14 to 87.50, with a mean Gfc of 79.1 ± 0.5. While the maximum number of dead retained branches on the butt log was 19, the mean number of dead branches was 3.18 ± 0.46, and 40 of the 77 trees had no dead branches.

Crown characteristics

The crown projection areas of the study trees ranged from 101.2 m^2 to 546.1 m^2, with a mean of 281.4 ± 10.7 m^2. Live crown ratios ranged from 0.397 to 0.867, with a mean of 0.602 ± 0.009. The isolated growth conditions resulted in asymmetric crowns, as determined with one-way ANOVA ($P = 0.0006$). This is likely due to prevailing winds, as the shortest radii were in the western and north-western radii, while maximum crown radius was 9.76 m, extending southward. Crown lengths had a mean of 14.38 ± 0.30 m, and ranged from 8.20 m to 22.70 m (Table 1.2). In the nine climbed trees, the mean number of live whorls was 39.1 ± 2.9, indicating that these trees experienced substantial crown expansion following release from the surrounding matrix. Mean branch diameter was 2.81 ± 0.09 cm, and maximum branch diameter was 17.3 cm.

Leaf area and growth efficiency

Branch leaf area was found to be well correlated with branch diameter ($R^2 = 0.9050$; Table 1.5). Relative depth in crown was not significant in predicting branch leaf area ($P = 0.599$). Several covariates were employed to predict PLA, though most were not significant. Rejected covariates included modified live crown ratio ($P = 0.513$; Valentine et al 1994), and live crown ratio ($P = 0.197$). Sapwood basal area ($P < 0.0001$) was significant, but was rejected due to the low correlation ($R^2 = 0.7748$) and the variability between the two increment cores from each tree. The final model included DBH and CPA (Table 1.6), which correlated well with PLA ($R^2 = 0.8972$). Predicted PLA ranged from 111.4 m^2 to 790.5 m^2, with a mean of 349.4 ± 20.2 m^2 (Table 1.4).

VINC was found to be well correlated with predicted PLA ($R^2 = 0.82$), and exhibited a fairly strong site effect, especially at the highly productive Dead River site (Table 1.9). Site effect was determined to be driven largely by tree age (Figure 1.7) rather than site productivity, as site index was found to be not significant when included in equation 4 (Figure 1.6). GE ranged from 0.092 $dm^3 \cdot cm^{-2}$ to 0.438 $dm^3 \cdot cm^{-2}$, with a mean of 0.220 ± 0.009 $dm^3 \cdot cm^{-2}$ (Table 1.4). Mean growth efficiency was lowest at the T39 MD site (0.15 $dm^3 \cdot cm^{-2}$), and highest at the Dead River Twp. site (0.31 $dm^3 \cdot cm^{-2}$). No discernable patterns were observed between growth efficiency and site index (Figure 1.6), however growth efficiency exhibited a decrease with tree age (Figure 1.7).

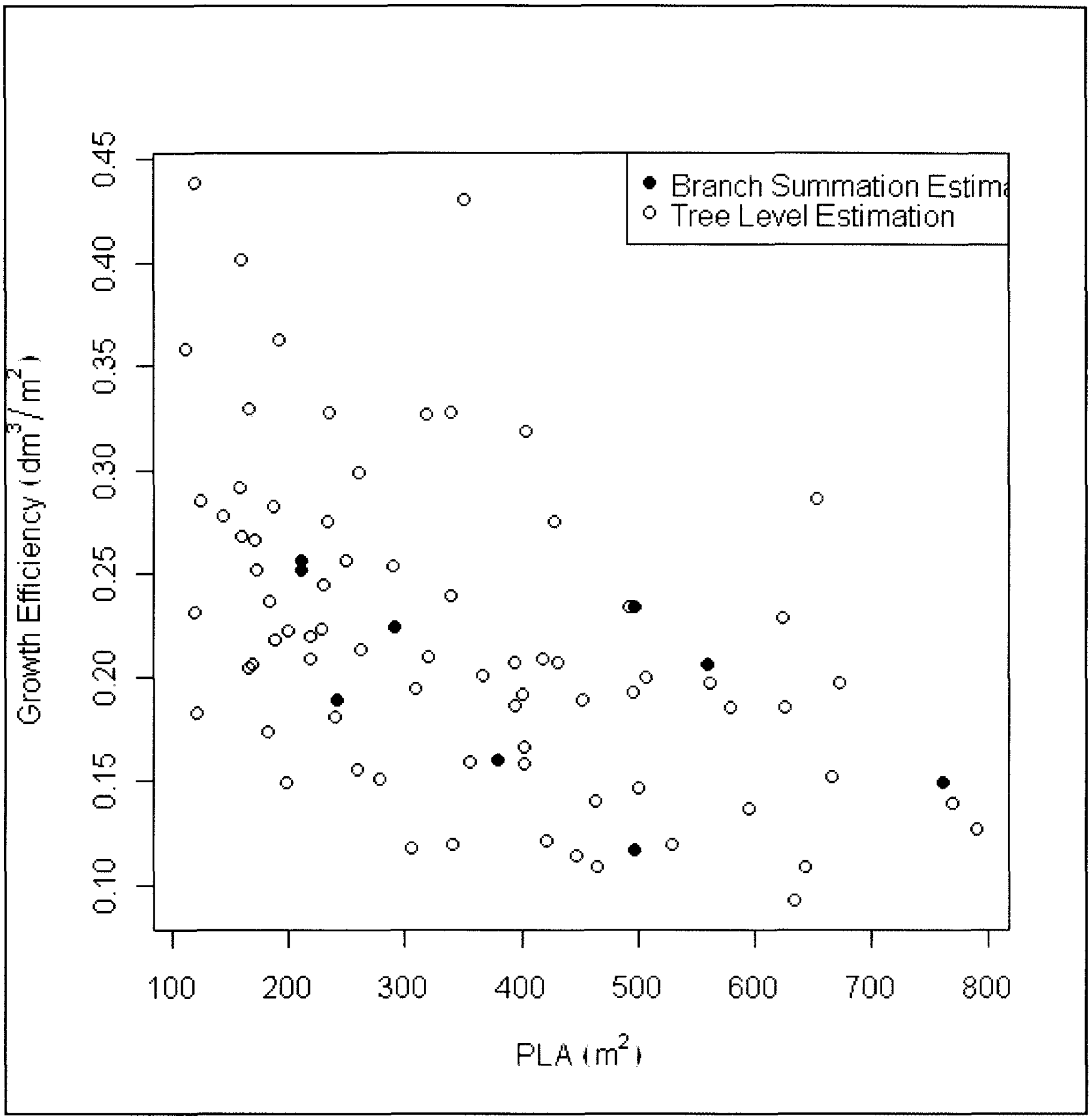

Figure 1.3. Growth efficiency (dm^3· m^{-2}) as a function of projected leaf area (m^2). Filled circles are climbed trees, and leaf area was estimated using the branch summation method. Open circles are leaf area estimates made using the whole-tree model.

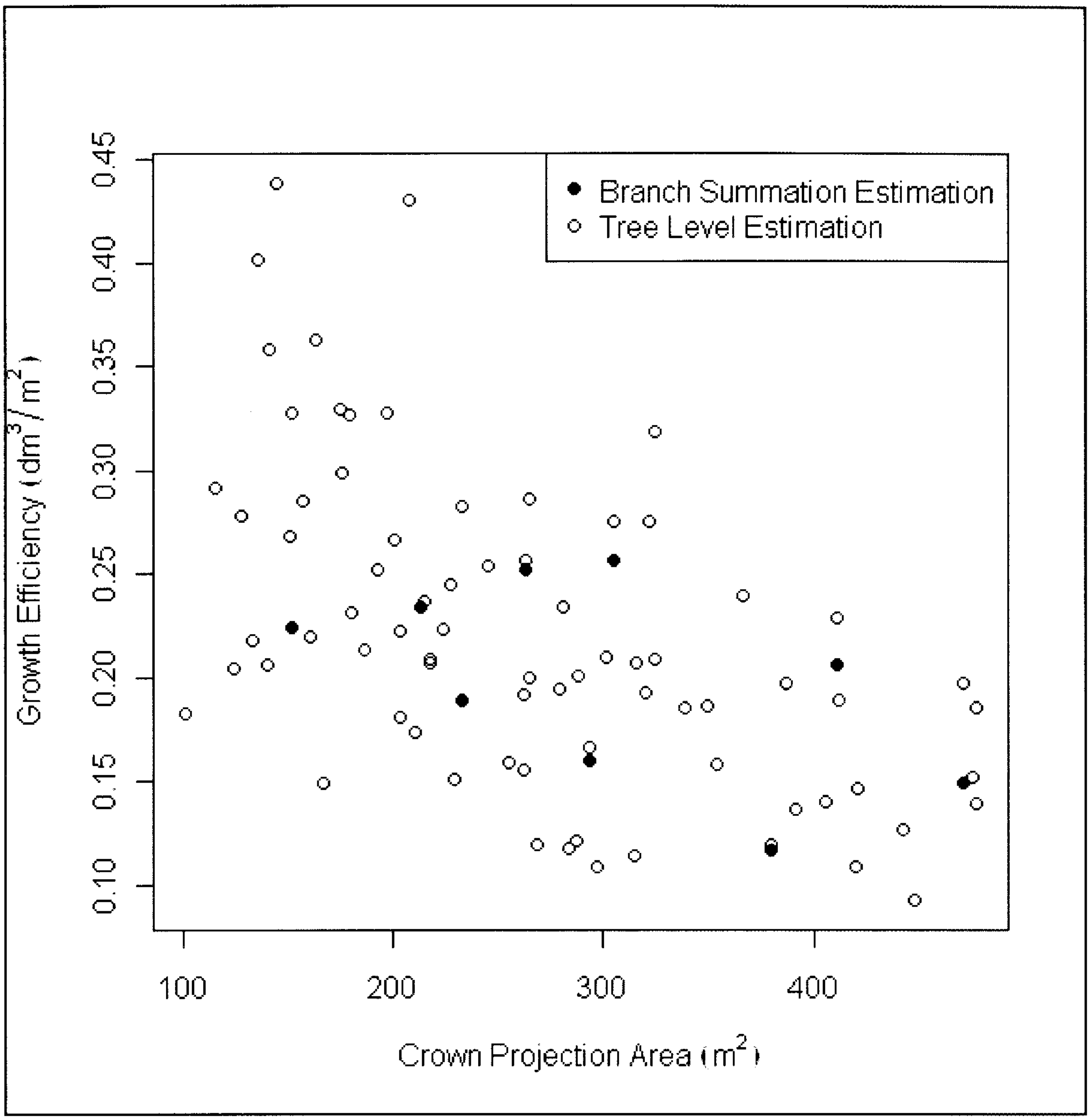

Figure 1.4. Growth efficiency ($dm^3 \cdot m^{-2}$) as a function of crown projection area (m^2). Filled circles are climbed trees, and leaf area was estimated using the branch summation method. Open circles are leaf area estimates made using the whole-tree model.

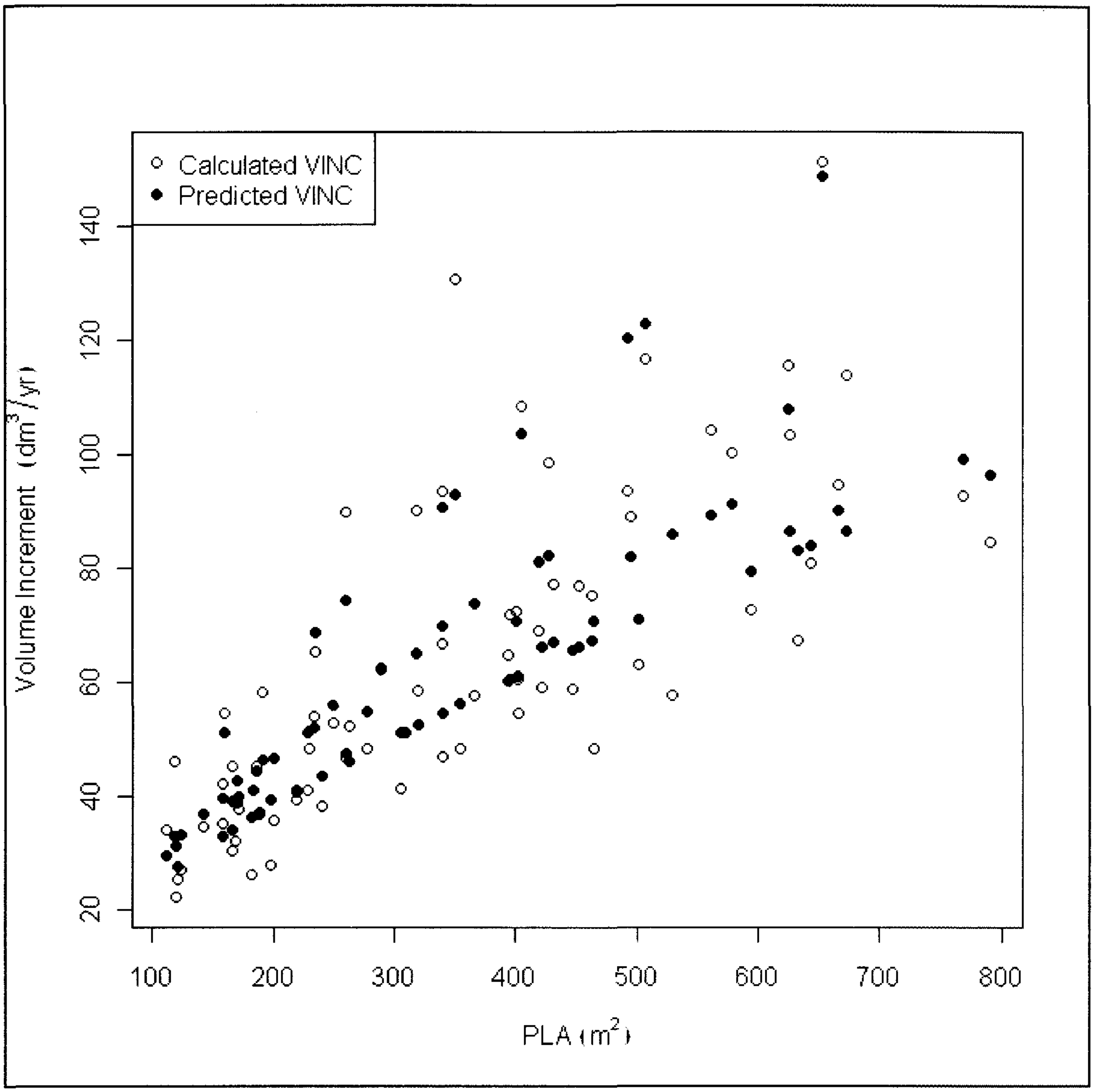

Figure 1.5. Annual volume increment (VINC, $dm^3 \cdot yr^{-1}$) as a function of projected leaf area (m^2). Open circles represent stemwood increment calculated with Honer's (1967) equation, filled circles represent fitted model [eqn 3].

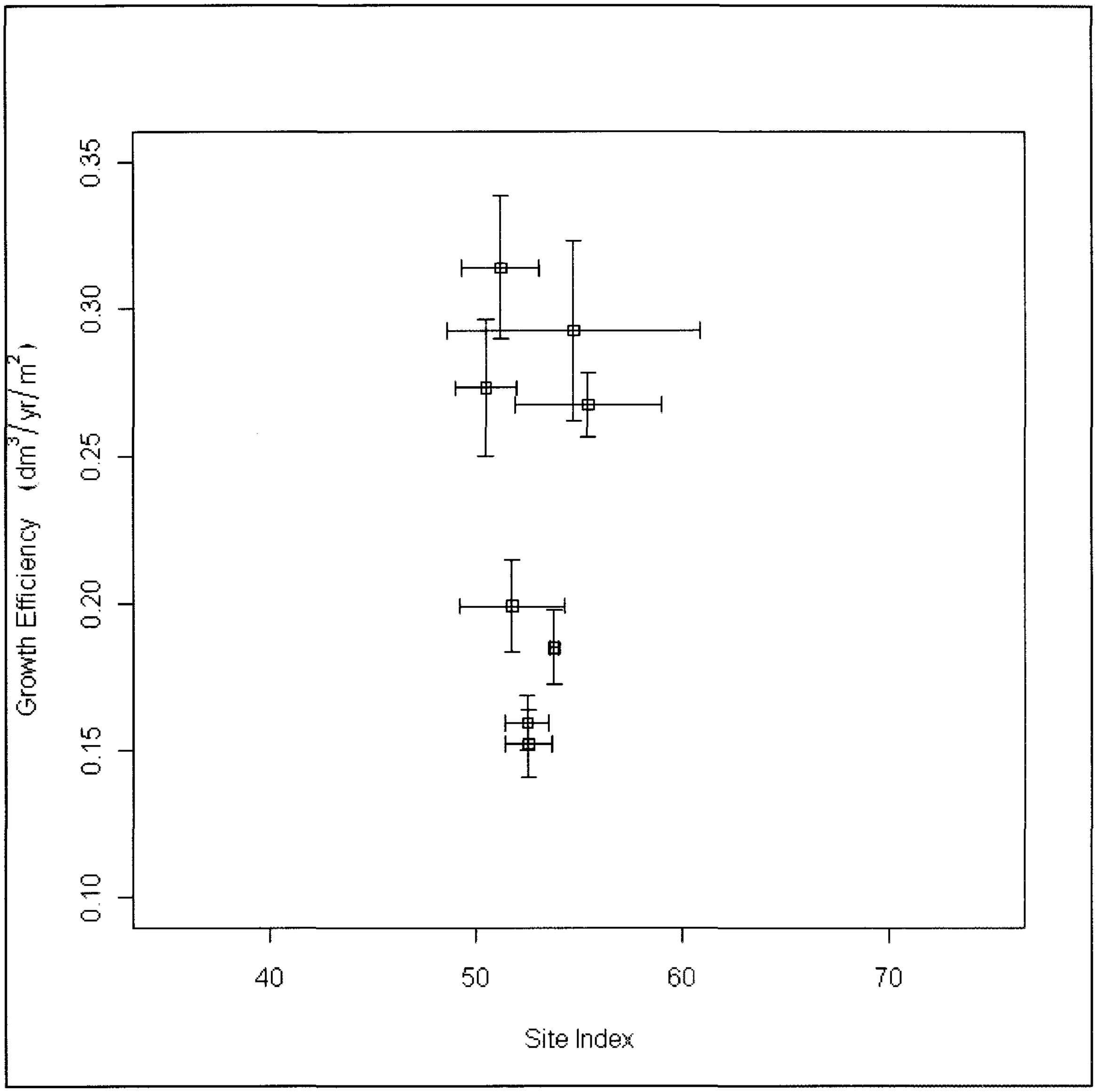

Figure 1.6. Growth efficiency as a function of site index (height in feet at base age 50). Grey circles represent individual observations, open squares represent site means with standard error bars.

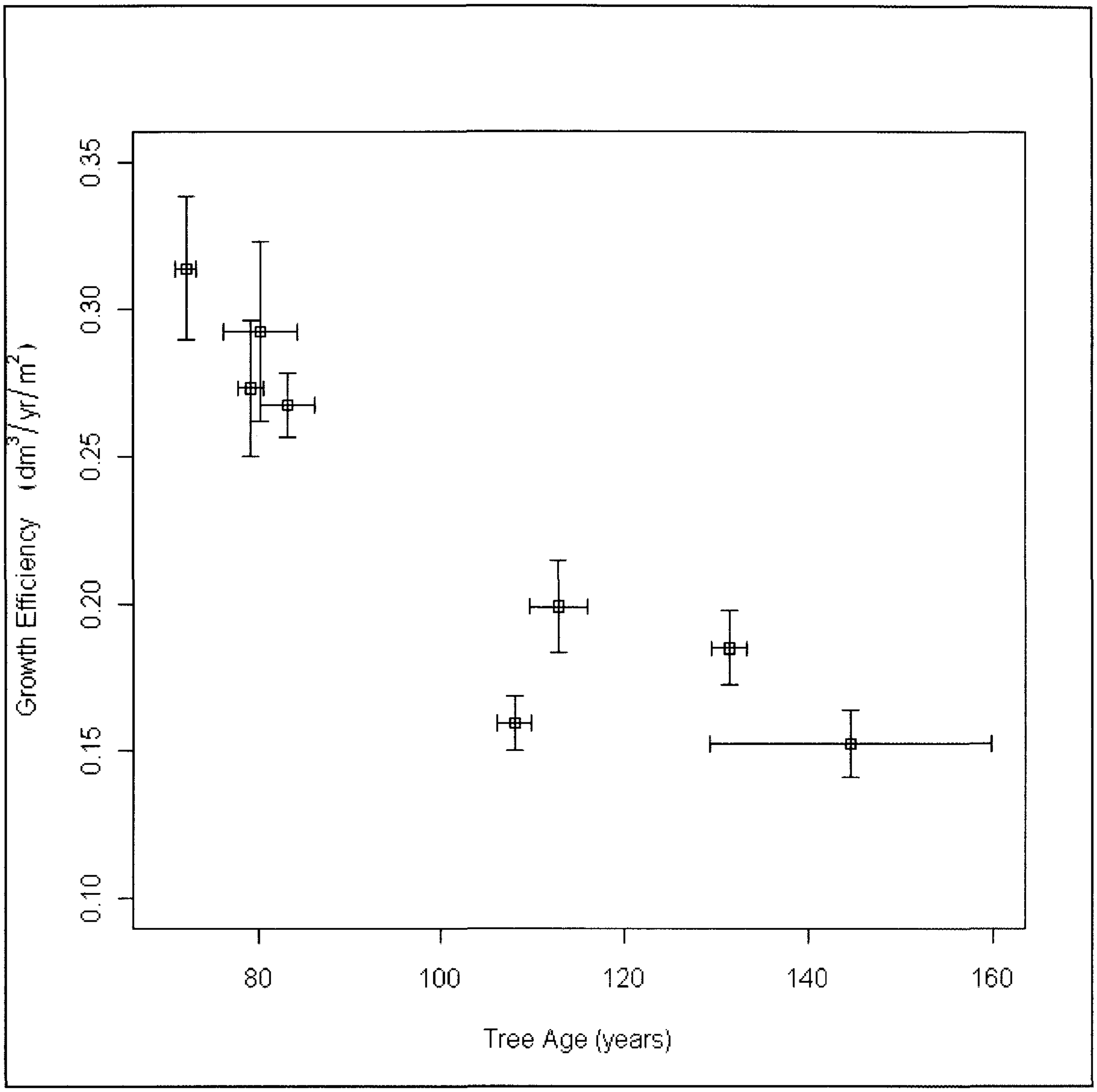

Figure 1.7. Growth efficiency as a function of tree age. Grey circles represent individual observations, open squares represent site means with standard error bars.

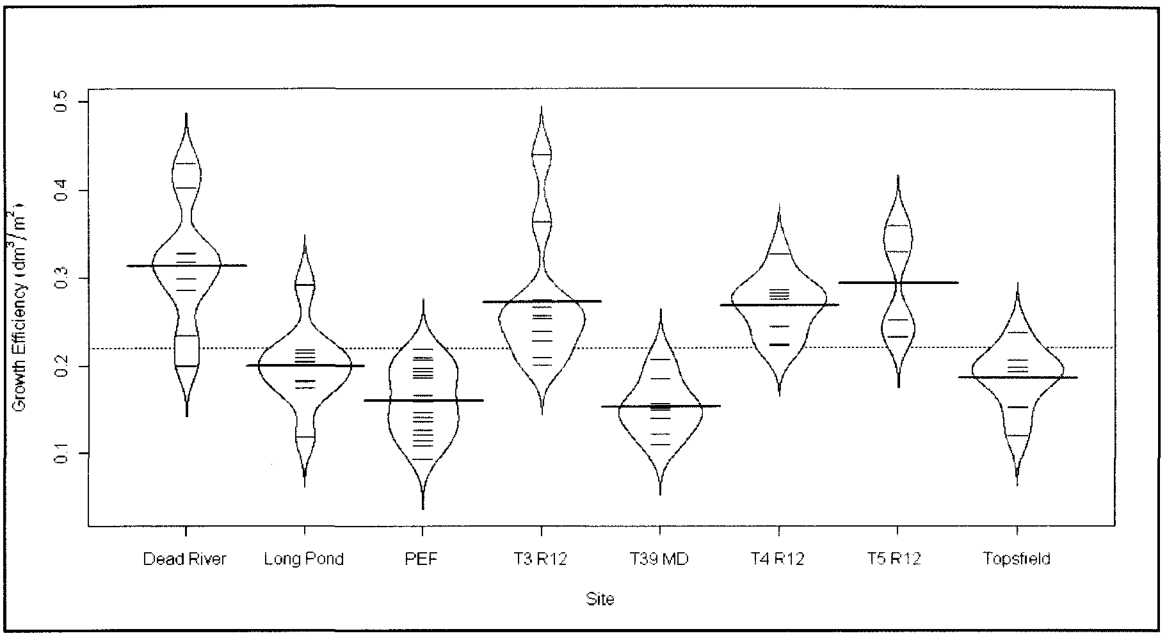

Figure 1.8. Beanplot of growth efficiencies by site. Small horizontal lines represent individual observations, and large horizontal lines represent site means. Dashed line across entire figure represents grand mean (0.22 $dm^3 \cdot m^{-2}$).

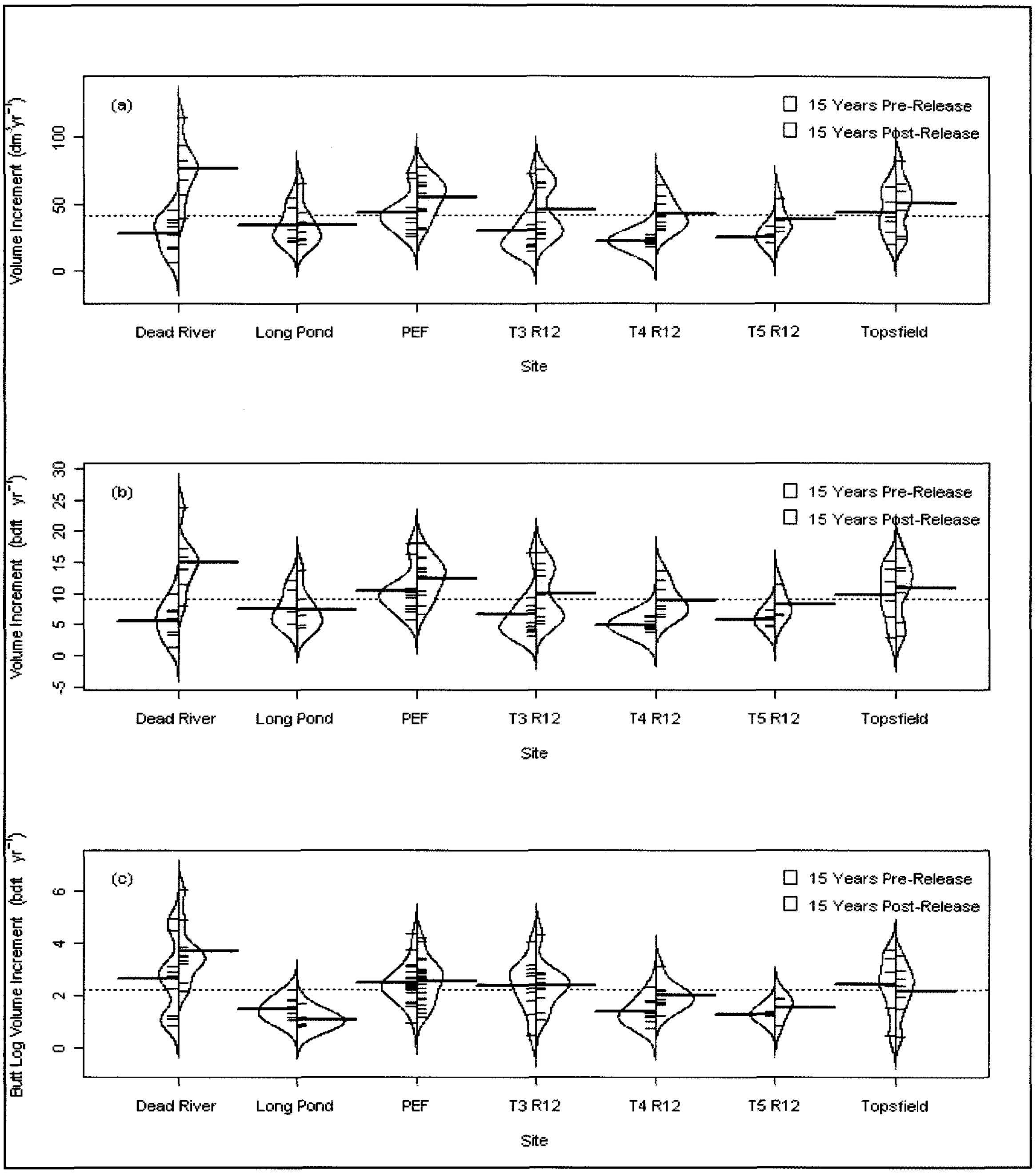

Figure 1.9. Beanplots of pre- and post- release volume increments by site, (a) for whole tree merchantable volume (dm^3 yr^{-1}), (b) Whole tree merchantable volume (bdft yr^{-1}), and (c) butt log merchantable volume (bdft yr^{-1}). Small horizontal lines represent individual observations, and large horizontal lines represent site means. Dashed line across entire figure represents grand mean

DISCUSSION

Tree growth and form

The significant increase in volume growth shows that white pine responds well to complete release. This is likely due to the unrestricted crown expansion, both vertically and laterally, afforded by this silvicultural system. While this coincides with the findings of Bevilacqua et al. (2005), the trees in the current study were much larger (44.8 ±1.2cm) at the time of release, indicating that white pine will continue to respond even at ages in excess of 100 years. While site factors likely accounted for some differences in response to release (Figure 1.9a), stand history may also have influenced growth response. Reserve trees at the only site to not exhibit a response, Long Pond, had small crowns and whole tree volumes, despite having the median number of years since release among all sites. This suggests that the highest quality or most vigorous trees were likely harvested at the time of release. The small crowns, combined with the relatively advanced ages found at this site were likely the driving factors limiting growth response. In contrast, the Dead River site release was an herbicide release trial, in which the best white pines were selected for retention. This, in combination with the high site productivity, as well as the youngest ages among all study sites, resulted in the largest growth response among sites.

Tree form was generally good, exhibiting moderate taper and few retained dead branches on the lower bole, which Fajvan and Seymour (1993) attributed to the "trainer" effect of growing amidst a matrix of dense, shade-tolerant conifers.

Crown characteristics

The unrestricted crown expansion that complete release facilitated in these trees has led to massive crowns, with some individual branches exhibiting diameters and lengths equal to that of a medium sized tree (Table 1.2). As such, the implementation of this silvicultural system requires very low reserve tree densities, likely fewer than 30 trees·ha^{-1}, in order to prevent crown competition and subsequent crown recession (Oliver and Larson 1990). This would allow average CPA to expand to over 300 m^2 before crown competition began, which would accommodate about 75% of the trees in this study. Some areas within the study sites exceeded this density, and crown closure had already begun, for the purposes of this study, trees in these areas were not considered. Crown form was generally representative of the archetypical white pine as depicted by Seymour and Smith (1987).

Leaf area and growth efficiency

Several studies have examined patterns of leaf area and growth efficiency in eastern white pine (Barker 1998, Pace 2003, Guiterman 2009, Weiskittel et al. 2009), however, these studies focused on trees growing within forest stands. Typically, the branch summation method involves felling a tree, then selecting easily accessible branches for sampling. Monserud and Marshall (1999) acknowledged that this could introduce sampling bias, and as such, selected only forest interior trees with fairly radially symmetric crowns. Forest interior tree crowns are shaped largely as a function of crown abrasion (Oliver and Larson 1990), a competitive process not experienced by the trees in the current research since their release. The resulting crown shape is likely influenced by abiotic factors, such as prevailing winds and sun angle, resulting in asymmetric crowns.

The use of a tree climber facilitated sampling from standing trees, which allowed branches to be selected using a random azimuth direction, thus reducing sampling bias. Branch-level leaf area prediction typically includes depth in crown as a covariate (Monserud and Marshall1999), to account for differences in specific leaf area, the measure of leaf area per unit mass, that occur due to varying light environments. Growing in relative isolation creates a much more uniform light environment throughout the crown, which explains why depth in crown was not significant in the branch PLA model.

PLA prediction was found to exhibit the best fit with the DCPA model, but other models performed acceptably (Table 1.6). This could be explained by the lateral expansion in the middle and lower branches within the crown, which supported most of the leaf area. While sapwood area may be the most biologically appropriate predictor of PLA (Shinozaki et al. 1964), the model with the poorest fit in this study was SACL, likely due to poor estimation of sapwood area using two increment cores, as sapwood width can be highly variable around the bole. The DCPA model provided the best fit, but CPA measurement is relatively labor intensive, and therefore may not provide the most practical model for field implementation. For this reason, the DCL model may be more appealing to forest managers, as crown length is easily measured with a hypsometer. The DCL model also has the added advantage in that future crown lengths can be predicted, as crown recession is very limited in completely released trees, and future heights can be predicted using site index curves.

VINC increased monotonically with PLA, albeit at a decreasing rate (Figure 1.5). The concave pattern coincides with VINC-PLA patterns seen in *Quercus petraea* (Assman

1970), *Pinus contorta* (Long and Smith 1990), and *Abies balsamea* (Gilmore and Seymour 1997). Predicted VINC for a PLA of 200 m^2 was about 46 $dm^3 \cdot yr^{-1}$, which is similar to the findings of Guiterman (2009) for stand grown eastern white pine. While the mixed-effects VINC model ($R^2 = 0.82$) had a better fit than the model that included age ($R^2 = 0.74$), age proved to be a significant covariate, whereas site index did not. This suggests that the differences between sites were primarily due to reserve tree ages, rather than estimates of site productivity based on site index equations.

GE decreased as PLA increased (Figure 1.3), which is consistent with the findings of studies involving other species (Long and Smith 1990, Gilmore and Seymour 1996, DeRose and Seymour 2009), and the same pattern was found with increasing CPA (Figure 1.4). This conforms to the idea that smaller, more compact crowns are the most efficient (Assmann 1970, Gilmore and Seymour 1996). Furthermore, Honer's (1967) volume equation does not account for branch wood, which neglects a significant component of the annual growth in trees with such massive crowns. Despite the decreasing trend in GE, the overall mean GE (0.22 $dm^3 \cdot cm^{-2}$, Figure 1.6) was similar to that of much smaller, forest grown eastern white pines (Guiterman 2009). Such isolated conditions results in much greater light availability along the sides of the crown, whereas even dominant forest grown trees receive most incoming sunlight from above. Site level GE (Figure 1.8) appears to be effected by age, with the 4 sites with the youngest trees exhibiting above average GE, and the four sites with the oldest trees exhibiting below average GE (Table 1.4), suggesting an age related decline, as found by Seymour and Kenefic (2002) in eastern hemlock (*Tsuga canadensis* L., Carrière). As exhibited in the VINC models, GE decreased monotonically with age (Figure 1.7), whereas no clear patterns were observed between GE and site index (Figure 1.6). This finding is somewhat contradictory to the findings of Hofmeyer et al. (2010), in which *Thuja occidentalis* GE was found to be significantly correlated with soil drainage, which may be an artifact of employing site index as an index of site productivity. In the case of this study, several assumptions were violated in the use of site index. Carmean et al. (1989) stated that proper application of site index equations requires the use of "free-growing, uninjured, dominant and codominant trees" from well-stocked-even aged stands. In this study, all of the climbed trees exhibited evidence of repeated weevil attacks, which would have resulted in the loss of height growth in the year of attack. Height growth of isolated trees may further be reduced by way of hydraulic limitation (Ryan and Yoder 1997), as open-grown trees are more susceptible to water stress. Finally, the ages of many of the trees included in this study were beyond the range of ages used to fit the site index equation (Carmean et al. 1989), which may have led to inaccurate results due to overextrapolation. This inaccuracy could be corrected for through destructive sampling and stem analysis, which would have allowed direct measurements of heights throughout the life of the tree.

CONCLUSIONS

The retention of mature eastern white pine trees as reserves allows for unrestricted crown expansion, both vertically and horizontally. This study has shown that this sustained increase in leaf area allows for a continued growth response, well after release, while providing a seed source and protection for future cohorts of pine within the mixed conifer regeneration matrix. For this system to remain effective, reserve density must be very low, likely less than 30 trees·ha^{-1}, to allow lateral and vertical crown expansion, so as to prevent future crown competition and subsequent recession. In selection of potential reserve white pine crop trees, priority should be given to vigorous, younger trees with clear, straight lower boles.

CHAPTER TWO

FINANCIAL PERFORMANCE OF ISOLATED EASTERN WHITE PINE RESERVE TREES IN THE ACADIAN SPRUCE-FIR FOREST OF MAINE, USA

ABSTRACT

The adaptation of eastern white pine (*Pinus strobus* L.) to persist as emergent trees makes them well-suited to retention as reserve trees in the mixed coniferous forests in the Acadian region of Maine. While there are many two-aged stands with pine reserves across the region, the financial performance of these trees has never been studied. We sampled 77 archetypal eastern white pine trees grown in relative isolation for 14 to 28 years from 8 forest stands throughout the spruce-fir region of Maine to assess financial performance. Increment core data and site index equations were used to reconstruct tree dimensions for every year post-release to the time of sampling. Future growth of each tree was projected from 2009 to 2050 employing relationships between leaf area, annual volume increment, and differing site productivity. Two scenarios were created: An unpruned scenario, in which the defect core was assumed to be the scaling end diameter of the butt log at the time of release; and a pruned scenario, in which the defect core was fixed at 15.24 cm. CantSim, a spreadsheet-based sawing simulation program was employed to estimate volumes and values by grade of eastern white pine (*Pinus strobus* L.) butt logs with a range of scaling and defect core diameters. A two-part polynomial regression model was then fit to predict butt log value. Using 5 year average wholesale prices, butt log values were then estimated with the two-part polynomial model, and top log values were estimated using existing volume equations. Financial performance was assessed using net present value (NPV) at the time of release. In the pruned scenario, NPV declined following release for all but fast growing, smaller trees, due to the high value of the trees when released. In the unpruned scenario, NPV tended to initially decrease, followed by a rapid increase as the trees began to accrue high value, knot-free lumber. On average, NPV peaked 52 years post-release, at which point trees had a mean diameter at breast height 68.8 (±2.9) cm, using a guiding rate of return of 4%.

To analyze the financial benefit of pruning directly, the differences in value between the pruned and unpruned scenarios were discounted back to the time of pruning, and pruning costs were subtracted. The peak mean benefit occurred 30 years after pruning, at which point the net present value was $23.67 (±2.83), using a guiding rate of return of 4%. Mean net present value of the pruning benefit remained positive for 101 years after pruning.

INTRODUCTION

In recent years, much attention has been given to ecosystem benefits of green-tree retention (Franklin 1989, Rose and Muir 1997, Acker et al. 1998). Silviculturally, trees retained after a regeneration harvest, or reserves, offer the benefit providing a seed source to future rotations, as well as casting shade, thus preventing establishment of undesirable intolerants (Miller et al. 2005). Little attention, however, has been given to the growth and financial performance of completely released reserve trees. With complete release, eastern white pine reserve tree crowns undergo unrestricted crown expansion, both vertically and laterally. This leads to a rapid increase in leaf area, the primary driver of tree productivity (Mainwaring and Maguire 2004). While increased growth rates undoubtedly increase the value of reserve trees, there has never been an investigation into whether the value growth can keep pace with discount rates when analyzed in terms of NPV.

Eastern white pine, although taxonomically a softwood, is treated in nearly the same manner as hardwoods by the forest products industry. As is done for hardwoods, special attention is given to grade recovery in the milling process due to the high price premium placed on the best grades of white pine products (Figure 2.1). Typical softwood milling is centered on sawing efficiency, as there are little price differences between structural softwood grades (Duvall, 2004). Grading of white pine is based on the appearance of the best face, as outlined by the Northeastern Lumber Manufacturers Association (NeLMA), and is limited by the maximum allowable defects, such as knot size and frequency, on a given board. The highest practical grade given to white pine is "D select & better," which only permits one knot, ½ inch in diameter or less, per surface foot (NeLMA, 1952).

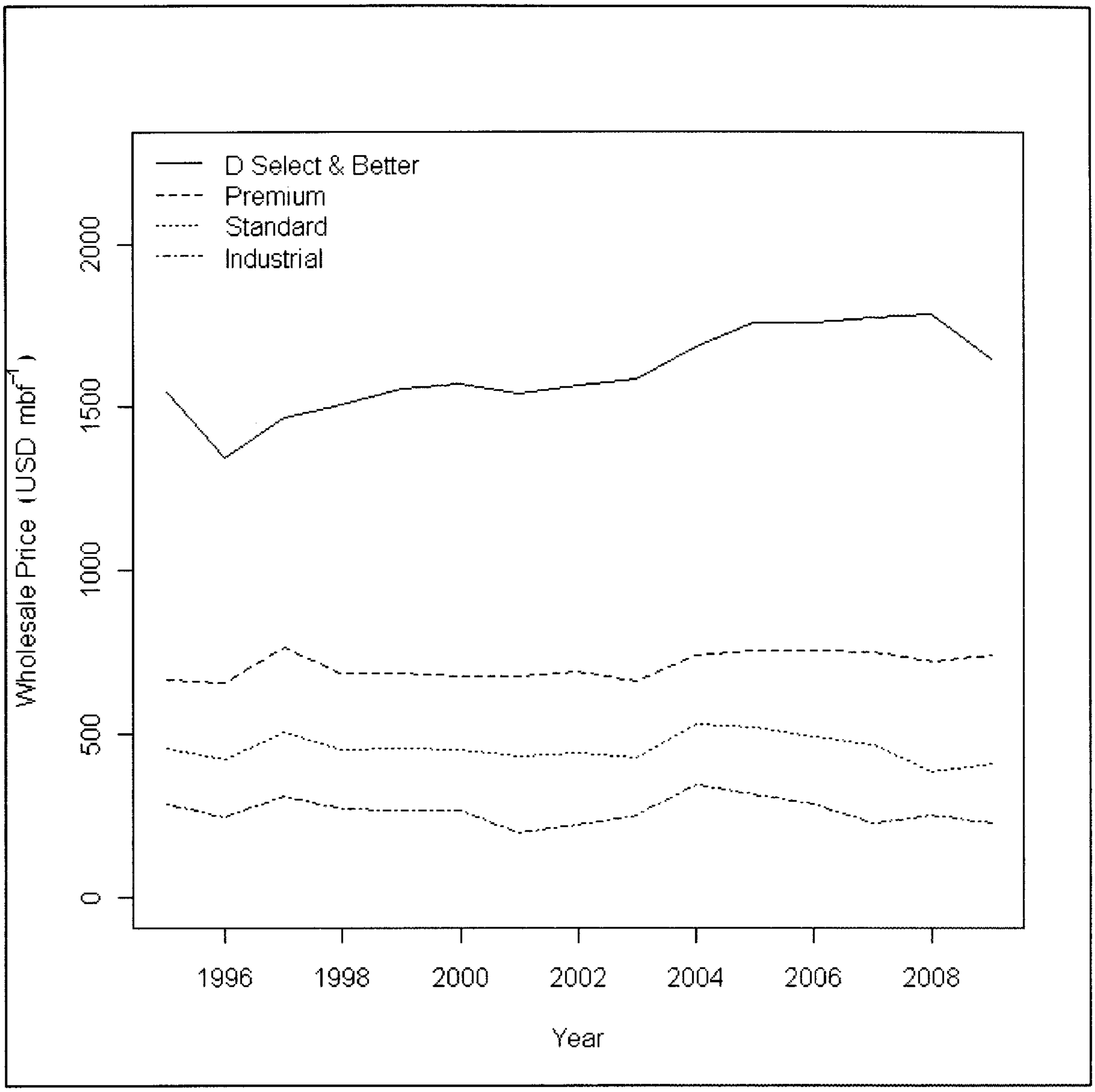

Figure 2.1. Prices of eastern white pine lumber (USD mbf^{-1}), by grade, for years 1995 to 2009 (source: Random Length Publications©, 2010).

As previously stated, the value of white pine depends largely on grade recovery. For this reason, white pine is often treated as a hardwood in respect to processing at a sawmill. There are two fundamental approaches to milling a log, one emphasizes volume recovery, which is employed at most softwood sawmills, the other focuses on value recovery, which is more common in hardwood and white pine sawmills (Thawornwong et al.

2003). The sawing method used to maximize value recovery is referred to as grade-sawing, which is designed to confine internal log defects to the fewest number of recovered boards as possible, resulting in high yields of high value products (Thawornwong et al. 2003).

Due to the premium placed on higher grade lumber, management practices should focus on minimizing the knotty core in eastern white pine. Poor natural branch shedding is, however, a problem associated with growing white pine crop trees, as pine tends to retain dead branches for more than 25 years, possibly as long as 73 years, resulting in an average of 60 defects to the valuable butt log (Wendel and Smith, 1990; Foster, 1957). Pruning is often employed to assuage this problem, but it involves a substantial investment. When applied to trees when they are young, but at least one log tall, it confines the defects in the butt log to a volume slightly larger than the diameter of the tree when pruned, known as the knotty core. Because of the investment involved with pruning can only be recouped by the growth of clear, valuable lumber over the knotty core, it is not recommended that this practice is employed on trees that are larger than 10 inches dbh (Seymour and Smith, 1987; Perkey, 1999). Branch occlusion in pruned white pine occurs rather rapidly, particularly if trees are free to grow. Rich (1957) found that although a scar may persist on the bark of a pruned white pine tree for years, clear wood is being grown over occluded branch stubs after an average of only 0.411 inches of radial growth. Fight, et al. (1992) performed a financial analysis of pruning ponderosa pine, which exhibits similar financial properties as white pine, in which a premium is placed on defect free lumber. They found that the break-even point for the investment was nearly

$11 per tree, based on a 4% guiding rate of return, with harvests occurring 30 to 70 years after pruning.

While pruning may be a financially sound practice, natural branch shedding can be used to augment the rate of return on the investment. Seymour (1992) found that when grown in combination with densely stocked spruce-fir stands, white pine develops a high quality, defect free bole as a result of the shading from the surrounding competition. Due to the relatively fast growth rate of white pine, they will generally attain a dbh of 20-30 cm as codominants over the course of a typical spruce-fir pulpwood rotation. The white pine component of the stand could then be retained through another rotation, amassing radial growth as emergent trees.

The objectives of this study were to (1) assess the post-release financial performance of eastern white pine reserve trees that were previously pruned or unpruned, and (2) assess the financial viability of pruning white pine that will at some point be completely released and retained as a reserve tree.

METHODS

Study sites

Eight forest stands throughout the spruce-fir region of Maine, USA were selected for this study (Table 2.1). Each stand was two-aged, with a mixed conifer regeneration stratum developing under a sparse canopy of heavily released eastern white pine reserve trees grown in relative isolation. The regeneration harvests that created this structure occurred between 1980 and 1994. Soils ranged from somewhat poorly-drained to very poorly-drained (Briggs, 1994).

Table 2.1. Study stand locations, harvest years, and soil drainage class (Briggs, 1994).

Site	Location	Harvest Year	Soil Drainage Class
Dead River Twp.	N 45° 12', W 70° 16'	1984	3 – Somewhat Poorly Drained
Long Pond Twp.	N 45° 36', W 70° 02'	1989	4 – Poorly Drained
Penobscot Experimental Forest, Compartment 2	N 44° 52', W 68° 39'	1984	3 – Somewhat Poorly Drained
Topsfield Twp.	N 45° 28', W 67° 51'	1992	4 – Poorly Drained
T3 R12	N 45° 56', W 69° 15'	1987	4 – Poorly Drained
T4 R12	N 45° 58', W 69° 11'	1991	3 – Somewhat Poorly Drained
T5 R12	N 46° 06', W 69° 15'	1994	5 – Very Poorly Drained
T39 MD	N 45° 01', W 68° 18'	1980	

Table 2.2. Attributes of eastern white pine reserve component of study stands at the time of sampling, with standard errors in parentheses.

Site	Density (stems ha^{-1})	Basal Area (m^{2} ha^{-1})	QMD (cm)
Dead River Twp.	9.2 (5.9)	1.96 (0.29)	52.2
Long Pond Twp.	20.0 (3.7)	2.41 (0.00)	39.2
Penobscot Experimental Forest, Compartment 2	23.3 (2.8)	5.54 (0.14)	55.0
Topsfield Twp.	9.2 (4.6)	1.94 (0.22)	51.9
T3 R12	41.7 (7.3)	6.54 (0.18)	44.7
T4 R12	32.5 (7.4)	3.88 (0.14)	39.0
T5 R12	15.0 (3.0)	1.74 (0.45)	38.4
T39 MD	30.0 (5.3)	7.31 (0.35)	55.7

Data collection

Fixed radius plots (0.1ha) were established to survey the reserve overstory. Each reserve tree was measured for dbh (1.37m) and crop tree suitability. Suitable trees were stratified into 10 cm diameter classes, and a proportional subset (n=77) were selected at random. Each tree in the subset was measured for total height, height to base of live crown, defined as the lowest contiguous live whorl, crown radii in six directions, diameter at breast height (1.37 m) and at the scaling end diameter at the top of the first 16 ft. log (5.18 m), and bark thickness in two locations at both 1.37 m and 5.18 m. Two increment cores were extracted at 1.37 m, and one at 5.18 m. Increment cores were scanned at 1200 dpi and measured with the WinDendro® software package (Regent Systems, Inc.).

Growth simulation

Site indices were calculated for each study tree using the Carmean, et al. (1989) equation. Heights were then estimated for each tree at every year from the year of release (Table 2.1) to 2050, the terminal year of the simulation. Tree diameters prior to 2008 were reconstructed using breast height increment core data. Honer's (1967) equation was then used to estimate whole tree volumes for each year from harvest date (table 2.1) to 2008. Estimation of diameters at breast height for the years 2009-2050 employed a leaf area based, three-step process. The projected leaf area of each tree in 2008 was estimated using the formula, as developed in chapter one of this study:

[1]

$$PLA = \beta_0 DBH^{\beta 1} CL^{\beta 2}$$

where PLA is projected leaf area (m^2), DBH is diameter at breast height (cm), and CL is crown length (m). Parameter estimates and fir statistics can be found in Table 2.4.

Table 2.3. Projected leaf area (m^2) equation [eqn 1] parameter estimates and fit statistics. SE -standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	p Value	RMSE	R^2
β_0	0.0316	0.0538	0.5787	55.65	0.87
β_1	1.9960	0.5303	0.0094		
β_2	0.5509	0.3795	0.1968		

Crown base was held constant throughout the simulation period, as the isolated reserves trees experienced no crown competition at the time of the study. Future crown lengths were simply the difference between crown base and predicted height. The estimated PLA was then used to predict the annual volume increment expected to accrue that year, using the nonlinear mixed effects model with the form as developed in chapter one of this study:

[2]

$$VINC = \beta_0 PLA^{\beta_1 + b_1}$$

where VINC is annual volume increment (dm^3), and b_1 is a site specific random effect . Parameter estimates and fit statistics can be found in Table 2.5, and estimated random effects can be found in Table 2.6.

Table 2.4. Annual volume increment (dm^3) equation [eqn 2] parameter estimates and fit statistics. SE -standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	*p* Value	RMSE	R^2
β_0	1.1074	0.3713	0.0004	11.045	0.82
β_1	0.69778	0.0583	< 0.0001		

Table 2.5. Random effects for the annual volume increment equation [eqn 2].

Site	b_1
Dead River Twp.	0.0583
Long Pond Twp.	-0.0041
PEF, Comp. 2	-0.0286
Topsfield Twp.	-0.0041
T3 R12	0.0136
T4 R12	0.0091
T5 R12	0.0001
T39 MD	-0.0211

The predicted VINC was then added to the previous volume to obtain the whole tree volume for the 2009. Finally, DBH in 2009 was calculated from Honer's (1967) equation solved for DBH:

[3]

$$DBH = \sqrt{\frac{VOL}{\beta_0} * \left(\beta_1 + \left(\frac{\beta_2}{HT}\right)\right)}$$

where VOL is whole tree volume (dm^3) and HT is tree height (m). This process was then repeated for each year until the end of the simulation period. Scaling end diameter of the butt log was then estimated using the Girard stem form class (Gfc), or the ratio of scaling end inside bark diameter to outside bark breast height diameter, measured for each tree. Stem form was held constant over the entire simulation period.

Two scenarios were simulated with respect to the knotty core in the butt log: (1) a hypothetical pruned scenario, in which the knotty core was assumed to be fixed at a diameter of 15.24 cm, and (2) an unpruned scenario, in which the defect core was assumed to be the scaling end diameter at the time of release. This approach is conservative, because most of the trees exhibited few, if any branches in the butt log, and likely had somewhat smaller knotty cores, and therefore would have contained recoverable clear lumber. For the pruned scenario, increment core data were used to determine the year in which each tree would have been 15.24 cm DBH, at which time pruning would have been performed.

Sawing simulation

Sawmill simulations were carried out on theoretical butt logs in 5-cm diameter classes ranging from 30 to 100 cm, and knotty defect cores ranging from 15 to 70 cm using a version of CantSim, a spreadsheet-based sawing simulation program (Benjamin, 2006), that was modified to maximize value recovery in knot-free sawlogs. Value recovery was maximized using a cant-sawing pattern in which the cant size was set to encompass the knotty core (Figure 2.2). If the knotty core exceeded maximum product width (30.48 cm), the cant was set equal to maximum product width. For value recovery optimization, the average prices from January 2005 to December 2009 for products graded D select & better were input in to the simulator, and linear programming was employed to optimize value for the opening face cut and each subsequent cut in the sawing pattern. Kerf size was set at ¼" (0.635 cm), and butt log length was set at 16 ft. (4.877 m). The graphical output was then visually assessed for grade recovery. Products with less than 33% of the best face within the knotty core were graded as D select & better, and all other products were graded as standard. Counts of all products were verified with the tabular output of the simulator. Each product was valued by grade and width using the average prices from January 2005 to December 2009 (Table 2.3). All prices were provided by Random Length Publications© (2010).

Table 2.6. Wholesale, mill delivered lumber prices and board feet·piece^{-1} for eastern white pine, by grade and product, used in sawmill simulation and tree valuation. All prices reflect average price for the period of January 2005 to December 2009 (Random Length Publications©, 2010).

Product	Price·mbf^{-1} (USD)	Board feet·piece^{-1}
D Select & better		
1 x 4	1511.33	5.33
1 x 6	1703.96	8.00
1 x 8	1511.58	10.67
1 x 10	1664.18	13.33
1 x 12	1896.47	16.00
Standard		
1 x 4	361.27	5.33
1 x 6	516.08	8.00
1 x 8	516.66	10.67
1 x 10	433.96	13.33
1 x 12	484.38	16.00
Average	462.46	--

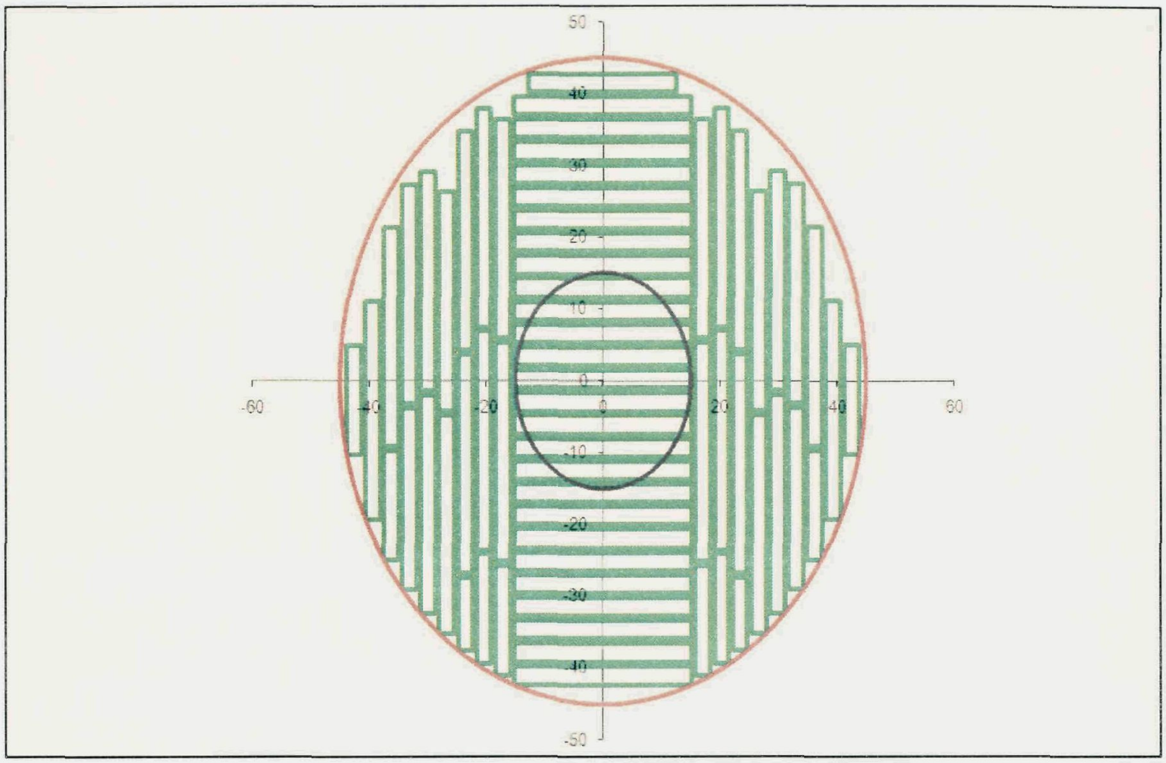

Figure 2.2. Example of graphical output of the CantSim sawing simulation program (Benjamin, 2006). Black inner circle demarcates knotty defect cor

Simulation results were then used to fit a two part equation to predict butt log value in US dollars, taking the form:

[4]

$$V_{pred} = \begin{cases} (DIA - KC) > 10, & \beta_0 + \beta_1 DIA^2 + \beta_2 KC^2 + \beta_3 DIA + \beta_4 KC \\ (DIA - KC) \leq 10, & \beta_5 + \beta_6 DIA^2 + \beta_7 DIA + \beta_8 KC \end{cases}$$

where V is the butt log value, in US dollars, DIA is the scaling end diameter, and KC is the defect core diameter. Parameter estimates and fit statistics can be found in Table 2.7. The two part equation was needed to account for the sharp decrease in value when KC is nearly as large or equal to DIA, which results in very little or no yield of D Select or better lumber.

Lumber recovery from the butt log was predicted by fitting an equation using the simulation results, which took the following form:

[5]

$$BDFT_{pred} = \beta_0 + \beta_1 DIA^2 + \beta_2 KC^2 + \beta_3 DIA + \beta_4 KC$$

where $BDFT_{pred}$ is lumber recovery, in board feet, and DIA and KC are as above. Parameter estimates and fit statistics can be found in Table 2.8. This prediction allowed for a correction to account for lumber recovery in slabs that result from butt log taper, which is not included in the CantSim sawmill simulator. The correction was calculated as follows:

[6]

$$V_{corr} = V_{pred} * \left(\frac{BDFT_{intl}}{BDFT_{pred}}\right)$$

where V_{corr} is corrected butt log value, $BDFT_{intl}$ is the butt log volume in board feet as calculated using the international ¼" rule, and V_{pred} and $BDFT_{pred}$ are as above.

Value of lumber above the butt log (V_{top}) was estimated by first estimating whole tree volume in board feet using the formula by Leak, et al (1970) for eastern white pine, then subtracting the volume of the butt log, as estimated with the International ¼" rule. The resulting board footage was then valued at the average price for standard grade lumber (Table 2.2), as specific products were unknown.

Whole tree values were then calculated by adding V_{corr} and V_{top}. These values were then adjusted for harvesting, trucking and milling. Based on discussions with local logging contractors and pine sawmills, who wish to remain confidential, costs associated with harvesting and milling costs were determined on a thousand board foot (mbf) basis. Harvesting and trucking was assumed to be \$162 mbf^{-1}, and sawing, planning, and drying were assumed to cost \$100, \$49, \$52 mbf^{-1}, respectively, for a total milling cost of \$201mbf^{-1}. The total cost of \$363 mbf^{-1} was subtracted from whole tree values to give standing values (V) for each tree in each year of the simulation period.

Table 2.7. Butt log value equation [eqn 4] parameter estimates and fit statistics. SE - standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	*p* Value	RMSE	R^2
β_0	2.0522	36.408	0.9552	28.75	0.997
β_1	-4.8216	1.0985	<0.0001		
β_2	4.0332	1.0020	0.0001		
β_3	0.2563	0.0078	<0.0001		
β_4	-0.2326	0.0124	<0.0001		
β_5	7.9513	20.902	0.7109	4.6542	0.997
β_6	2.3312	1.0778	0.0534		
β_7	-3.4989	0.5989	0.0001		
β_8	0.0688	0.0081	<0.0001		

Table 2.8. Butt log volume (bdft) equation [eqn 4] parameter estimates and fit statistics. SE -standard error; RMSE – root mean squared error; R^2 – generalized coefficient of determination.

Parameter	Estimate	SE	*p* Value	RMSE	R^2
β_0	4.9624	8.3607	0.5542	6.60	0.999
β_1	-0.9559	0.2523	<0.0001		
β_2	-0.4951	0.2301	0.0339		
β_3	0.1276	0.0018	<0.0001		
β_4	0.0047	0.0029	0.1037		

Analysis

Net present value for individual trees(NPV_{tree}) were calculated as follows:

[7]

$$NPV_{tree} = \frac{V_t}{(1+i)^t}$$

where NPV_{tree} is net present value in US dollars, V is the value in year t, i is the guiding interest rate of return, and *t* is the number of years from present. Analysis performed for both pruned and unpruned scenarios, using time of release (TOR) as V_0. For this analysis, pruning was considered to be a sunk cost, and therefore was not considered. This assumption was made to accommodate a single management decision, whether or not to retain trees as reserves regardless of past investments.

To assess the financial benefit of pruning, the value of the unpruned trees was subtracted from the value of the pruned trees to give pruning benefit (PB). PB was then discounted back to the time of pruning (TOP) using:

[8]

$$NPV_{prune} = \frac{PB_t}{(1+i)^t} - PC$$

where NPV_{prune} is the net present value of the financial benefit of pruning, PB_t is the pruning benefit in year t, i is the guiding interest rate of return, t is the number of years from TOP, and PC is pruning cost. Pruning costs were assumed to be $4.21 for each tree

(O'Hara et al, 1995). Guiding rate of return (GRR) was held at 4%, except where otherwise noted.

RESULTS

Average post-release financial performance

Average NPV for unpruned trees (Figure 2.3) initially declined when the guiding rate of return (GRR) was 5 or 6%, but rose slightly, followed by a decline when GRR was 3 or 4%. This is followed by a marked increase for GRR of 3, 4, and 5% at the 24th year post-release, at which point the amount of clear wood rapidly accumulated around the defect core began to increase the value in the butt log. While NPV does increase at year 24 at a GRR of 6%, the discounted value never recovers to the value at release. With a GRR of 5%, maximum NPV of $33.14 occurs at year 43, however this is only a $2.39 increase over the value at release. With a GRR of 4%, NPV peaks at year 52, at which point the mean DBH is 68.8 (±2.9) cm. With a GRR of 3%, peak NPV appears to past the projected time frame in this simulation.

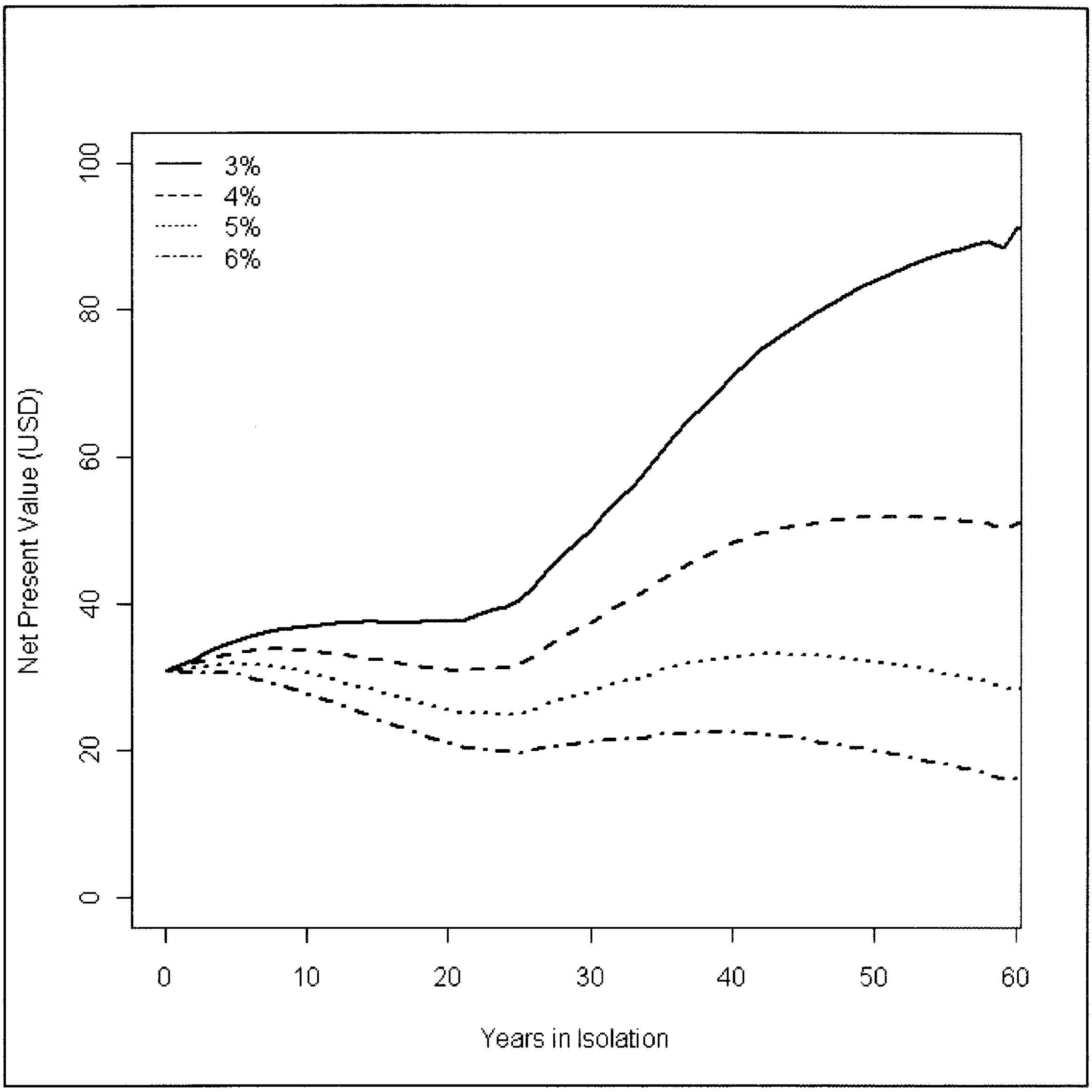

Figure 2.3. Net present values for unpruned scenario averaged for all study trees, under guiding rates of return ranging from 3 to 6% and 0 to 60 years after complete release. Values were discounted to time of release.

Average NPVfor pruned trees declines immediately following release, regardless of GRR (Figure 2.4). Peak NPV may occur well before the time range analyzed in this simulation. Although declining rapidly, average NPV 60 years post-release for pruned trees is 33% greater than that of unpruned trees.

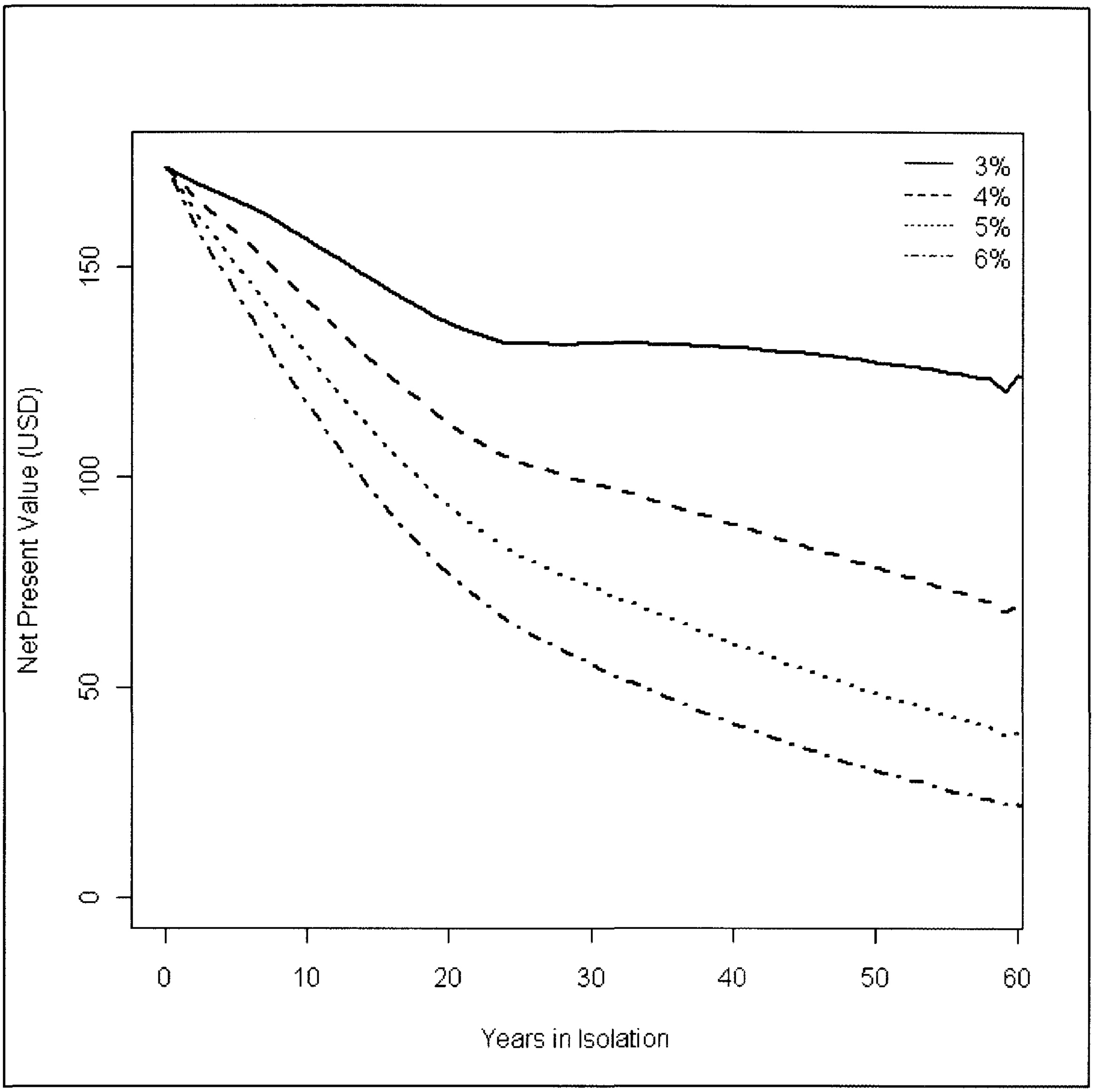

Figure 2.4. Net present values for pruned scenario for all study trees, under guiding rates of return ranging from 3 to 6% and 0 to 60 years after complete release . Values were discounted to time of release.

Financial analysis by site and tree characteristics

Trends in post-release NPV vary by site, tree size, and whether pruning occurred or not. In unpruned trees (Figure 2.5), site productivity and value at release influence initial trajectory of NPV. In the most productive sites, Dead River and T3 R12, NPV shows a generally increasing trend. At the least productive site, Long Pond, the general trend is either flat or slightly decreasing. Sharp initial decreases in NPV can be seen in both the PEF and T39 MD, both of which have high quadratic mean diameters (Table 2.2), and thus high initial values, combined with generally lower productivity. All sites exhibit a disconnect in NPV reflecting the time at which the scaling end diameter exceeds the defect core diameter by 10 cm or more, at which point trees begin to accrue higher value clear lumber.

In pruned trees (Figure 2.6), a nearly universal trend of decreasing NPV is seen. This trend was not seen in the highly productive Dead River site, as rapid growth of valuable clear lumber offset the effect of discounting.

When trees are grouped by both DBH at release and average 20 year post release diameter increment, large trees exhibit the most rapid initial decline in NPV among the unpruned trees (Figure 2.8), due to their relatively high initial value. Small and medium trees, regardless of growth rate, tend to exhibit a nearly flat response to release, followed by a rapid increase at which point they begin to accumulate higher grade lumber at a rate nearly equal to the 4% GRR.

Released pruned trees grouped by the same initial tree characteristics (Figure 2.9) show a decline in NPV, with the exception of fast growing small trees, which exhibit a slight increase in NPV, and fast growing medium-sized trees, whose values seem to keep pace with discounting at a 4% GRR. Direct comparison between the two simulated pruning treatments (Figure 2.10) shows that while post-release NPV generally decreases for pruned trees, and increases for unpruned trees, NPV remains substantially higher in pruned trees for several decades, except in smaller trees.

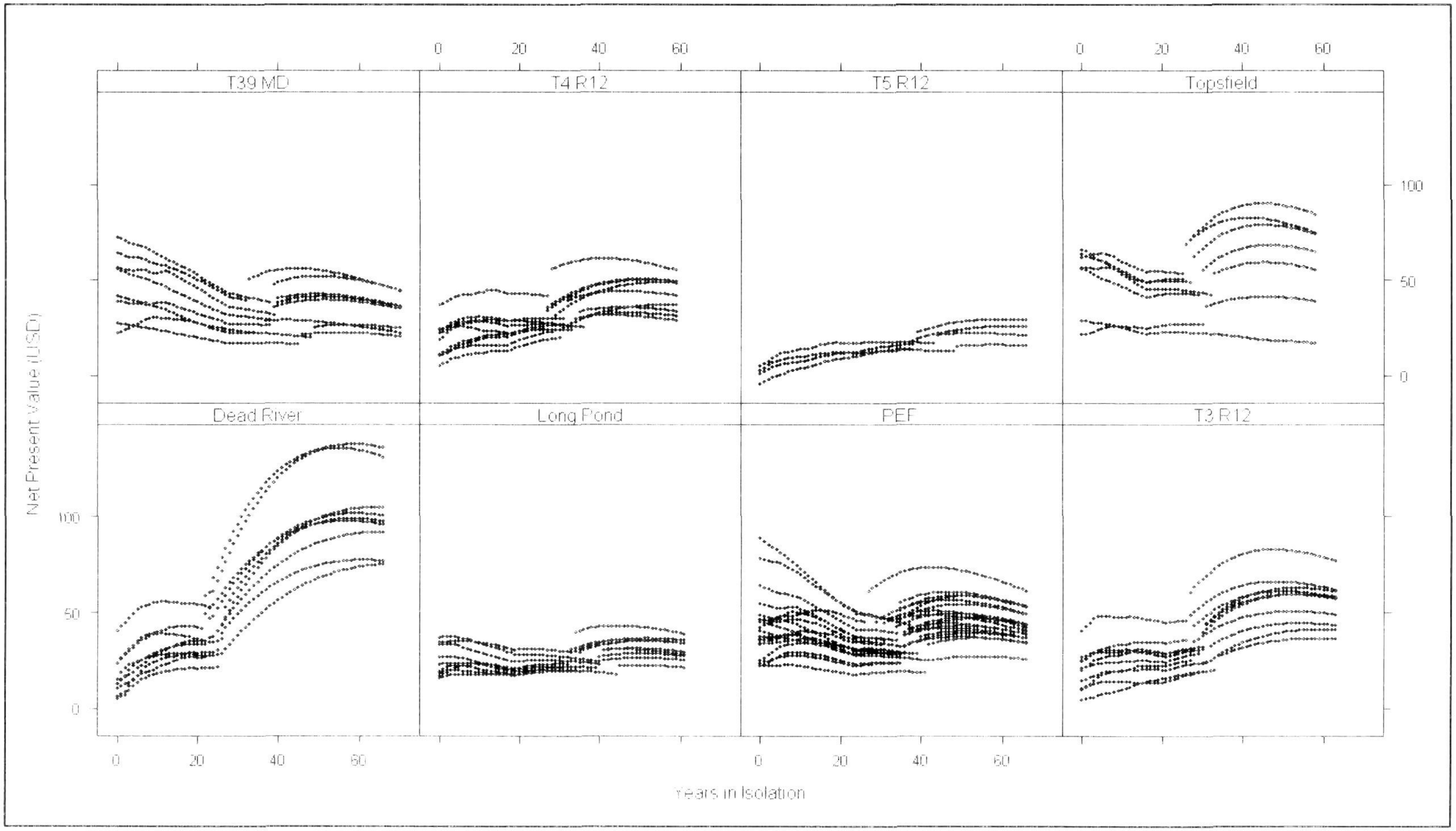

Figure 2.5. Post-release net present values for every tree in unpruned scenario, grouped by site. Guiding rate of return was fixed at 4% and values were discounted to time of release.

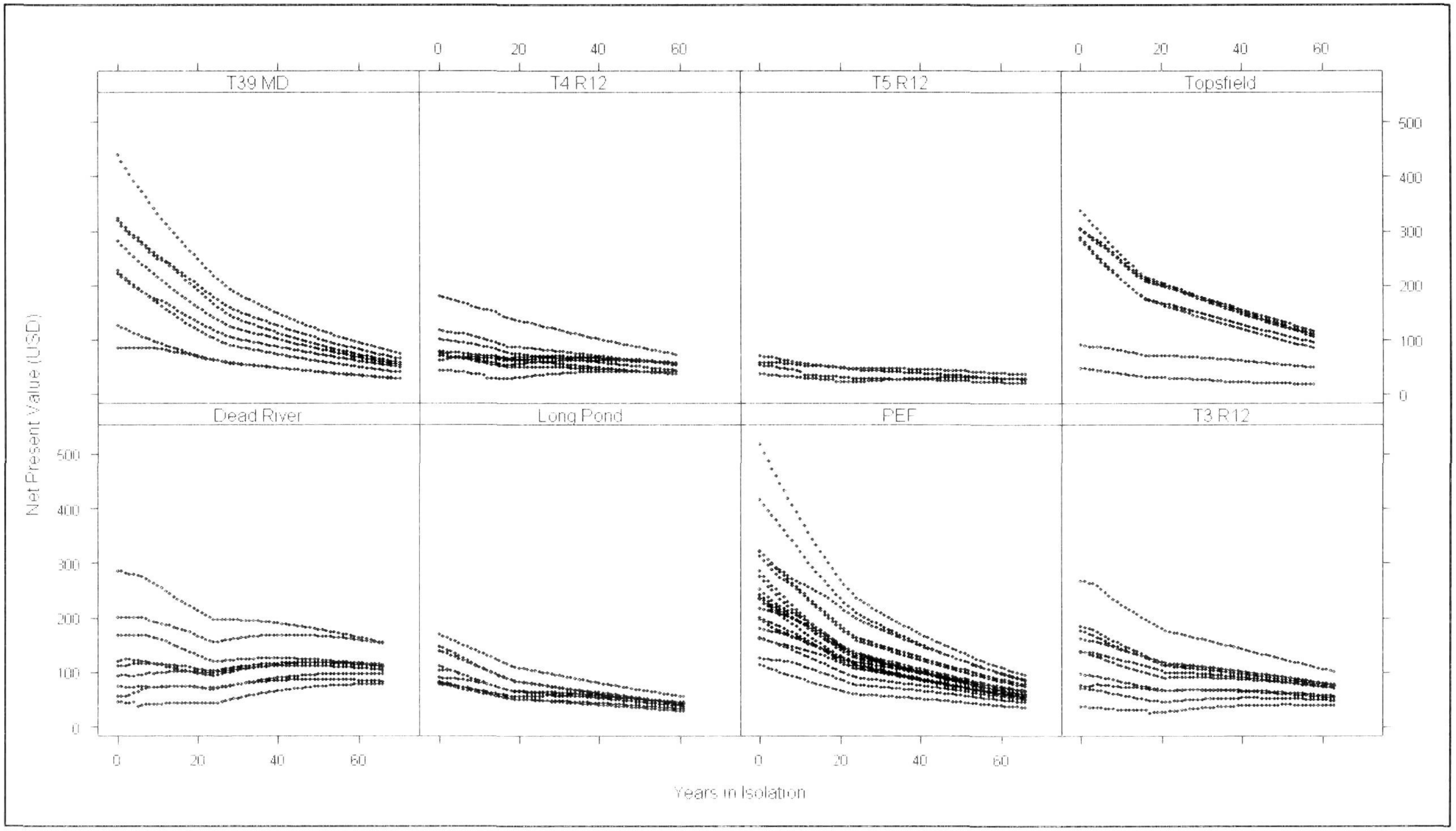

Figure 2.6. Post-release net present values for every tree in pruned scenario, grouped by site. Guiding rate of return was fixed at 4% and values were discounted to time of release.

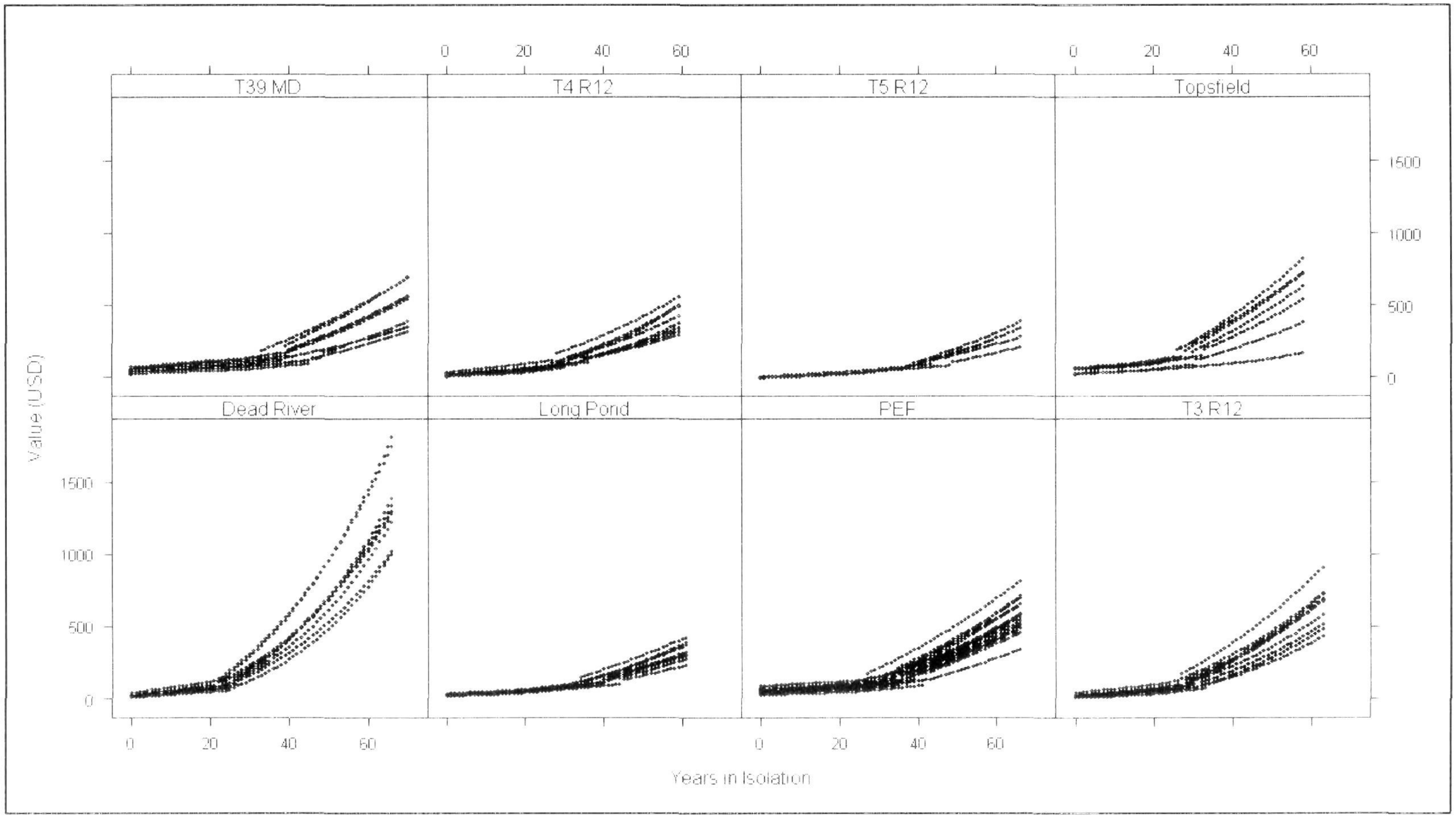

Figure 2.7. Post-release undiscounted values for every tree in unpruned scenario, grouped by site.

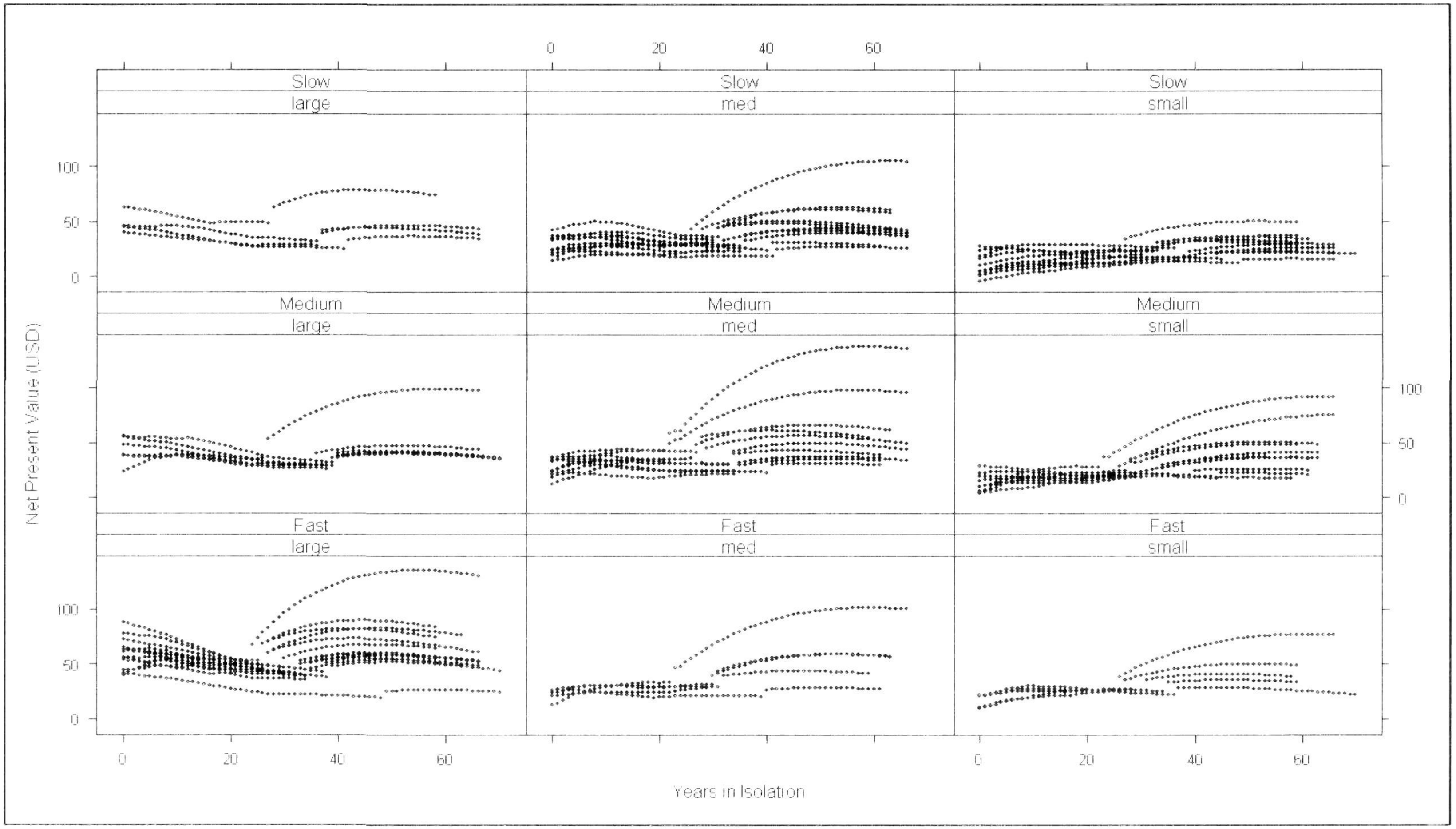

Figure 2.8. Post-release net present values for every tree in unpruned scenario, grouped by tree characteristics. Upper group boxes are relative post-release growth rates (Slow < 0.53 cm yr^{-1}, 0.53 cm yr^{-1} < Medium < 0.68 cm yr^{-1}, Fast > 0.68 cm yr^{-1}), and lower group boxes refer to relative diameters at release (small < 30.0 cm, 30.0 cm < medium < 39.0 cm , large > 39.0 cm). Guiding rate of return was fixed at 4% and values were discounted to time of release.

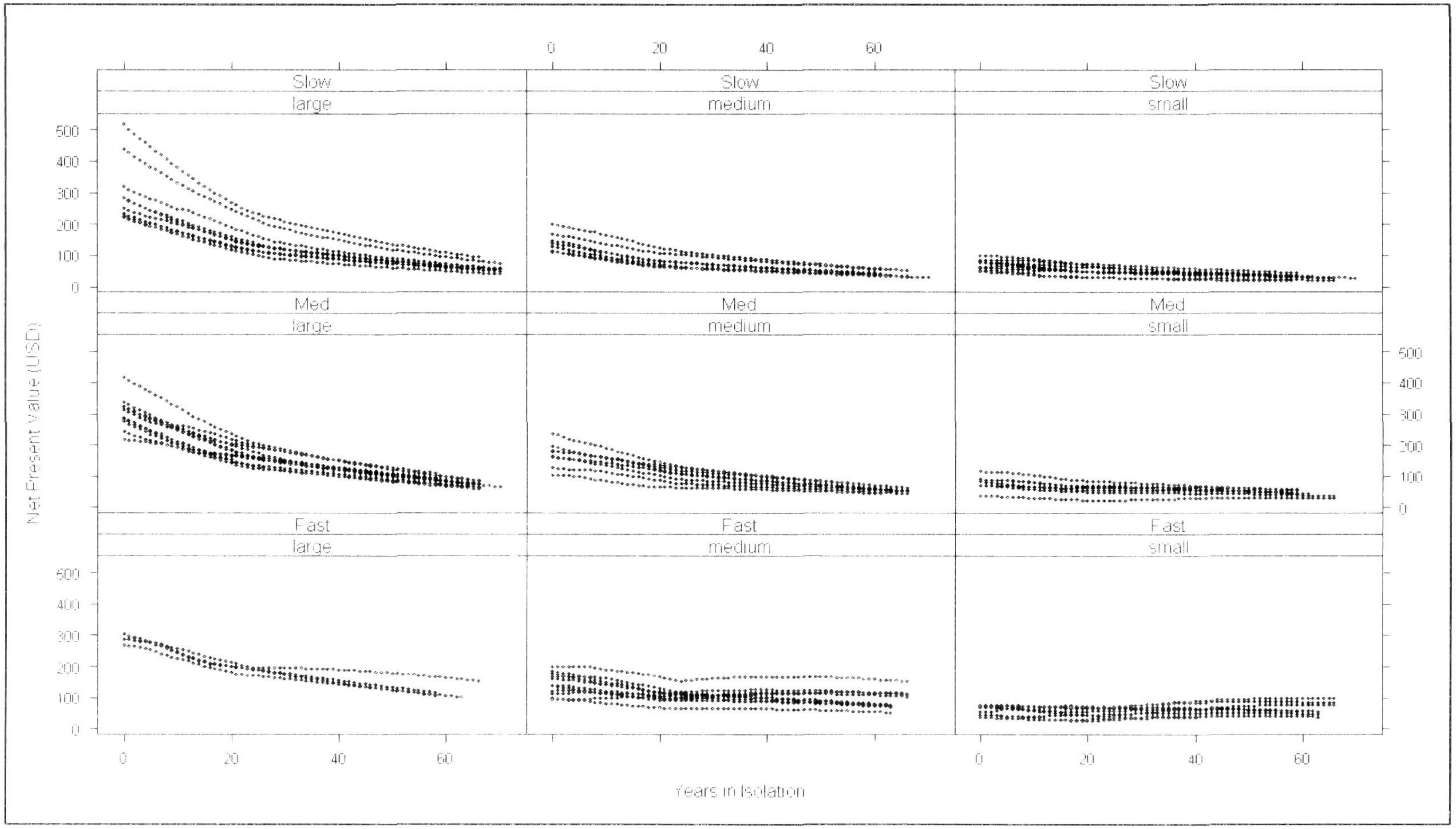

Figure 2.9. Post-release net present values for every tree in pruned scenario, grouped by tree characteristics. Upper group boxes are relative post-release growth rates (Slow < 0.53 cm yr^{-1}, 0.53 cm yr^{-1} < Medium < 0.68 cm yr^{-1}, Fast > 0.68 cm yr^{-1}), and lower group boxes refer to relative diameters at release (small < 30.0 cm, 30.0 cm < medium < 39.0 cm , large > 39.0 cm). Guiding rate of return was fixed at 4% and values were discounted to time of release.

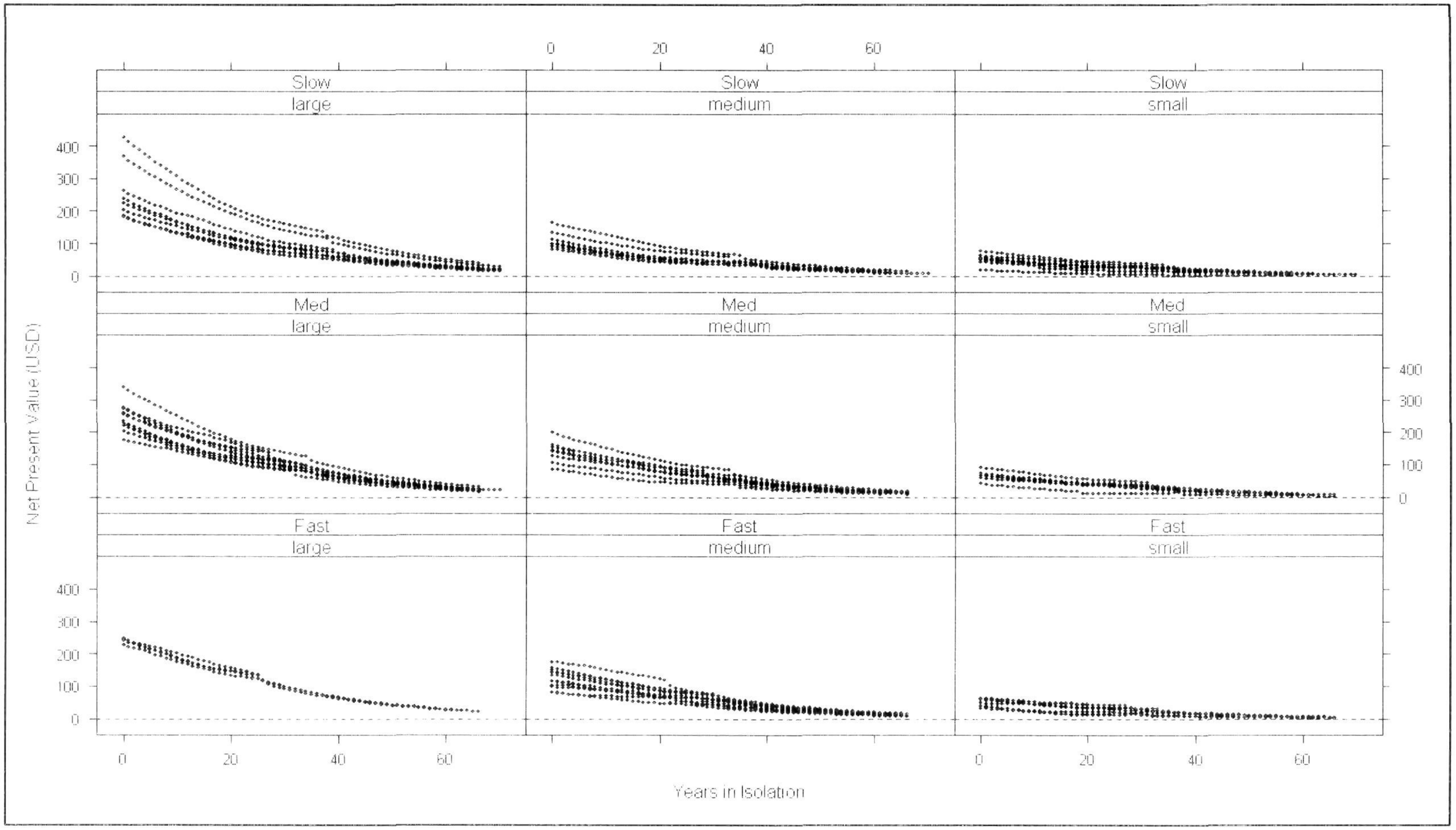

Figure 2.10. Differences between post-release net present values of pruned and unpruned scenarios, for every tree, grouped by tree characteristics. Upper group boxes are relative post-release growth rates (Slow < 0.53 cm yr^{-1}, 0.53 cm yr^{-1} < Medium < 0.68 cm yr^{-1}, Fast > 0.68 cm yr^{-1}), and lower group boxes refer to relative diameters at release (small < 30.0 cm, 30.0 cm < medium < 39.0 cm , large > 39.0 cm). Guiding rate of return was fixed at 4% and values were discounted to time of release.

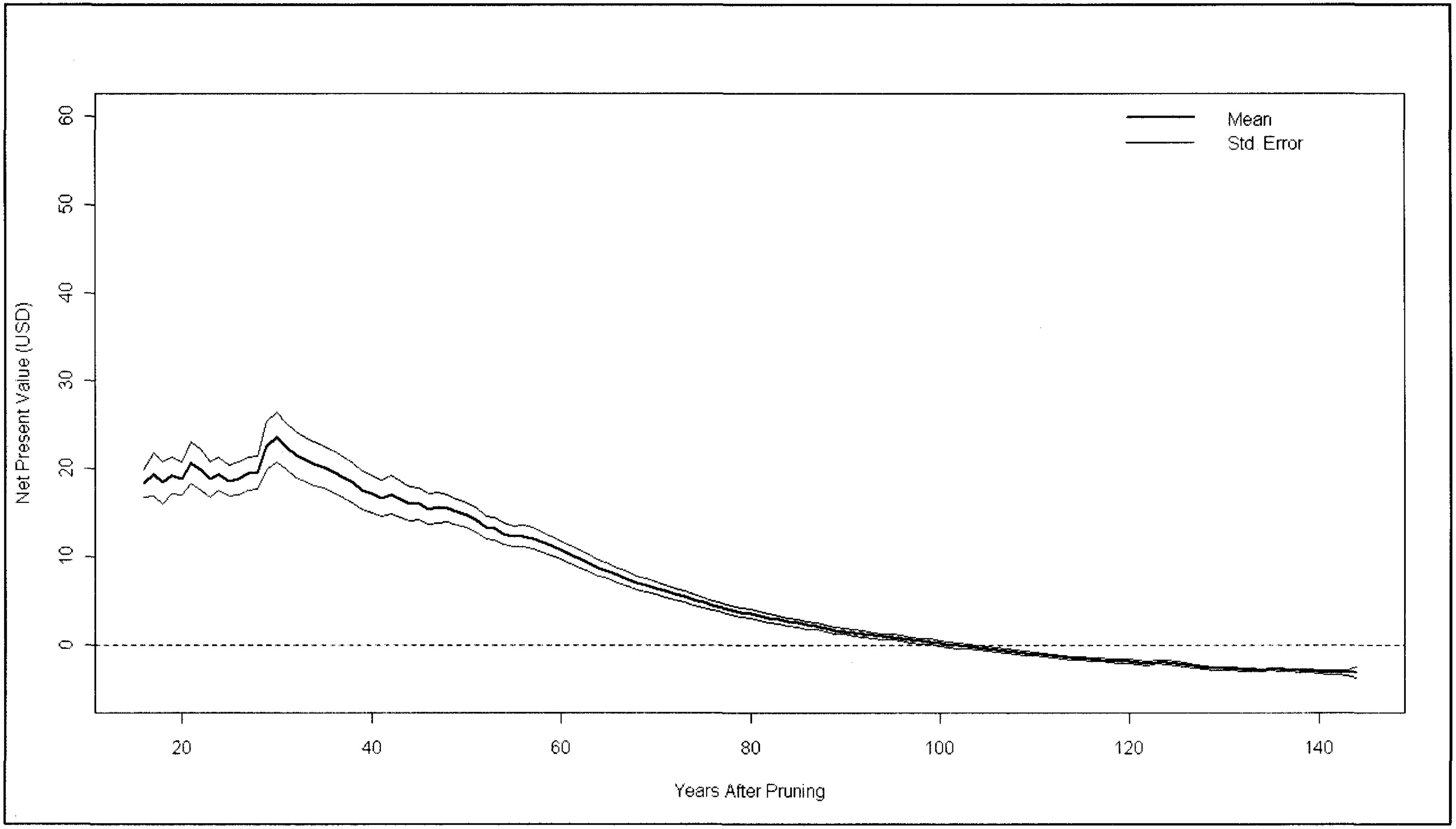

Figure 2.11. Net present values of financial benefit of pruning, assuming a guiding rate of return of 4% and values discounted to time of pruning. Grey dot series represent individual trees. Heavy solid line represents the mean, thin solid line shows the standard error. Dashed horizontal line represents zero net present value, below which pruning investments exceed the benefit.

Financial analysis of pruning investment

The analysis of pruning benefit (Figure 2.11) shows that the NPV of the mean PB reaches its maximum value 30 years after pruning a 15.24 cm tree, at \$23.67 (±2.83). This was true for GRR of 3% and 5%, as well, with NPVs of \$33.05 (±3.78) and \$16.71 (±2.12). The NPV of PB remained positive for GRR of 4% and 5% for 101 and 76 years, respectively, and remained positive for the entire simulation period at a 3% GRR.

DISCUSSION

Financial viability of reserve white pines with and without pruning

The financial performance of heavily released, mature eastern white pines appears to be favorable for extended periods, depending on tree conditions at the time of release. The primary factors affecting performance appear to be initial size and vigor. With the exception of the Long Pond site, sites with smaller trees at the time of release (Table 2.9) exhibited the most favorable increases in NPV (Figure 2.5). The Long Pond site, while having the lowest mean initial diameter, also exhibited the lowest mean post-release radial increment (0.20 ± 0.03 $\mathrm{cm \cdot yr^{-1}}$), which led to value growth nearly equal to discounting rate. Despite having the third largest initial mean diameter, the Topsfield site also performed well, due to vigorous post-release growth, with a mean radial increment of 0.33 ± 0.06 $\mathrm{cm \cdot yr^{-1}}$. Larger trees from less productive sites, such as T39 MD and the PEF, had peak NPV at the time of release, but smaller trees at these sites performed well, with peak NPVs as much as 54 years post-release (Table 2.10).

Table 2.9. Summary statistics of tree diameters at time of release by site.

Site	Mean	Standard Error	Minimum	Maximum
Dead River Twp.	42.0	2.9	29.4	57.1
Long Pond Twp.	39.4	1.2	34.0	44.6
PEF, Comp. 2	50.5	1.6	41.5	66.6
Topsfield Twp.	50.2	3.6	27.7	55.4
T3 R12	41.7	2.6	36.0	90.8
T4 R12	36.6	1.4	30.6	45.9
T5 R12	30.5	1.5	27.4	33.6
T39 MD	54.8	5.3	35.1	57.8

Table 2.10. Post-release year in which net present values (NPV) with a 4% guiding rate of return peaks, and undiscounted values for study trees in that same year.

		Unpruned			Pruned		
Tree	Site	Year	NPV (USD)	Value (USD)	Year	NPV (USD)	Value (USD)
2	PEF	0	45.55	45.55	0	250.29	285.29
3	PEF	54	27.26	226.64	0	86.37	114.03
4	PEF	49	49.72	339.72	0	207.45	236.22
5	PEF	53	46.96	375.39	0	235.73	275.10
6	PEF	49	43.27	295.65	0	165.11	197.47
7	PEF	0	89.00	89.00	0	474.12	518.41
10	PEF	0	46.70	46.70	0	212.74	252.11
12	PEF	52	47.75	367.05	0	211.29	243.65
13	PEF	52	39.46	303.31	0	135.72	164.49
14	PEF	0	64.18	64.18	0	293.17	324.28
15	PEF	0	48.93	48.93	0	173.25	233.86
18	PEF	43	50.96	275.20	0	158.20	218.81
20	PEF	0	78.36	78.36	0	371.51	417.57
21	PEF	50	37.51	266.60	0	95.05	127.42
22	PEF	0	54.53	54.53	0	282.23	313.35
23	PEF	47	41.97	265.16	0	165.06	201.47
27	PEF	42	48.80	253.39	0	127.38	161.04
29	PEF	46	56.57	343.65	0	142.08	179.93
30	PEF	43	73.78	398.42	0	290.19	322.55
31	T39 MD	0	56.43	56.43	0	297.53	319.39
32	T39 MD	0	55.79	55.79	0	254.30	283.07
34	T39 MD	0	72.83	72.83	0	161.31	441.11
36	T39 MD	0	64.08	64.08	0	286.60	323.00
37	T39 MD	0	42.06	42.06	0	204.54	228.19
38	T39 MD	0	27.71	27.71	0	50.83	127.52
39	T39 MD	51	39.84	294.46	0	179.28	221.86
40	T39 MD	9	30.54	43.47	0	34.69	86.50
41	Topsfield	45	79.05	461.74	0	237.19	338.11
42	Topsfield	47	68.45	432.43	0	166.28	284.35
44	Topsfield	45	41.36	241.59	0	40.09	91.90
45	Topsfield	42	82.78	429.84	0	199.07	304.03
46	Topsfield	0	28.80	28.80	0	-2.64	49.17
47	Topsfield	45	90.24	527.10	0	199.72	304.68
49	Topsfield	0	66.35	66.35	0	171.18	289.24
51	Long Pond	51	35.31	260.94	0	66.71	104.57
53	Long Pond	48	36.17	237.62	0	65.84	91.42

		Unpruned			Pruned		
Tree	Site	Year	NPV (USD)	Value (USD)	Year	NPV (USD)	Value (USD)
54	Long Pond	3	37.85	42.58	0	97.59	138.54
55	Long Pond	2	33.74	36.50	0	111.12	147.52
56	Long Pond	52	36.76	282.57	0	49.63	83.28
57	Long Pond	50	26.39	187.52	0	51.70	79.37
58	Long Pond	50	28.84	204.93	0	72.15	111.52
59	Long Pond	44	43.16	242.43	0	109.25	169.86
60	Long Pond	4	23.72	27.75	0	60.36	81.38
61	T4 R12	51	50.31	371.80	0	54.65	71.27
62	T4 R12	46	44.33	269.32	0	99.34	118.03
63	T4 R12	55	48.89	422.73	0	55.56	71.54
64	T4 R12	57	37.18	347.75	0	35.79	45.01
65	T4 R12	50	50.68	360.18	0	62.59	76.79
66	T4 R12	46	35.87	217.91	0	83.91	101.19
67	T4 R12	47	32.90	207.84	3	41.66	74.53
68	T4 R12	42	31.79	165.09	0	60.15	79.58
69	T4 R12	41	61.44	306.80	0	156.14	181.72
71	T5 R12	53	22.33	178.49	0	44.05	58.82
73	T5 R12	58	16.22	157.75	0	44.20	53.43
74	T5 R12	62	26.03	296.22	0	30.24	38.13
75	T5 R12	59	29.68	300.25	0	60.95	70.54
76	T3 R12	54	59.58	495.37	0	120.57	139.26
77	T3 R12	54	44.63	371.05	0	83.65	97.85
78	T3 R12	59	41.31	417.88	0	56.05	70.82
79	T3 R12	48	83.12	546.13	0	250.14	268.11
80	T3 R12	58	36.70	356.94	0	28.67	38.27
81	T3 R12	50	61.19	434.86	0	122.64	138.00
82	T3 R12	53	63.03	503.90	0	168.27	185.55
83	T3 R12	52	59.58	457.98	0	160.63	177.24
84	T3 R12	48	66.27	435.42	0	144.92	160.90
85	T3 R12	52	50.71	389.77	4	64.33	91.24
86	Dead River	55	135.93	1175.30	0	271.37	286.73
87	Dead River	59	99.27	1004.11	0	153.02	168.99
88	Dead River	63	104.98	1242.22	2	110.95	134.77
89	Dead River	59	101.89	1030.58	4	103.91	136.92
91	Dead River	59	138.05	1396.42	0	186.02	201.38
92	Dead River	57	97.96	916.10	1	83.51	98.99
93	Dead River	61	77.64	849.45	0	64.39	74.76
94	Dead River	64	91.98	1131.94	8	55.67	98.92
95	Dead River	66	75.36	1003.04	0	36.36	45.58

Despite the variation between sites with regard to NPV, trees from all sites became valuable by the end of the simulation period (Figure 2.7). This is especially tree of the highly productive Dead River site, where all trees were approaching or exceeding undiscounted values of 1,000 USD.

The conservative assumption that the knotty core diameter is equivalent to the scaling end diameter of the butt log was employed due to the lack of knowledge of internal defects, but knotty cores were likely considerably smaller, as live crown bases were generally well above the butt log. This would have a significant effect on whole tree value, as the presence of clear lumber would have substantially increased the initial value as the butt log, which accounts for more than half the value of the entire tree (Figure 2.11). Internal knowledge could have drastic effects on recommended retention period for the reserve trees, as growth rates cannot withstand the scrutiny of discounting when initial values are high. This is evident in the pruned scenario in which the trees already too valuable to justify retaining, as tree growth could maintain value increases greater than the 4% GRR.

The financial analysis of pruning was confounded in this study by the differing periods of time between time of simulated pruning and time of release, which ranged between 16 and 107 years. While peak profits occur at only 30 years after pruning, the sustained net profit period of 101 years, when a GRR of 4% is employed, suggests that reserve pines could be retained though a second rotation of spruce and fir, and a net profit from pruning would still be realized. This would allow for coordination of harvesting activities, thereby reducing damage to the surrounding stand when felling the large reserve pine. At this time, a new cohort of reserves, already selected and pruned, would be retained as reserves.

Sawmill simulation

The use of sawmill simulators to maximize value recovery of a log can be a valuable tool, but only if the sawyer has *a priori* knowledge of the size of the defect core. Recently, non-destructive log scanning methods have been used to determine the internal defects of a log. X-Ray computed tomography (CT) is of particular interest, as it provides a high resolution and is relatively efficient (Thawornwong et al. 2003). CT scanning is performed by a rotating X-Ray machine that provides a series of two-dimensional images at specified increments along the length of the log. Internal defects are easily discerned due to differences in densities in knots, voids, heartwood, and sapwood (Rinnhofer et al., 2003).

The information provided by CT scanning was found to improve yield recovery by 6.6% when applied by sawyers (Rinnhofer, 2003). When information on the location and size of the knotty core, as provided by CT scanning, was combined with sawing optimization from AUTOSAW, value recovery was increased as much as 11% (Todoroki, 2005). Gains in productivity associated with CT scanning and computer aided sawing optimization are substantial, and merit further review. Hodges et al. (1990) found that the increase in value recovery as a result of implementing CT scanning into the milling process would offset the cost of the investment in the scanning equipment in southern U.S. hardwood mills. Based on the similarities in processing of white pine and hardwoods, it stands to reason that high volume New England white pine mills could also profit from this technology.

Pruning, along with detailed record keeping, also has the potential to give sawyers *a priori* knowledge of the approximate size of the defect core. This knowledge, combined with a database of value-maximizing simulated sawing patterns, could also yield substantial improvements in value recovery, without the added cost of expensive CT scanners, or the reduced efficiency associated with simulations tailored to each individual log.

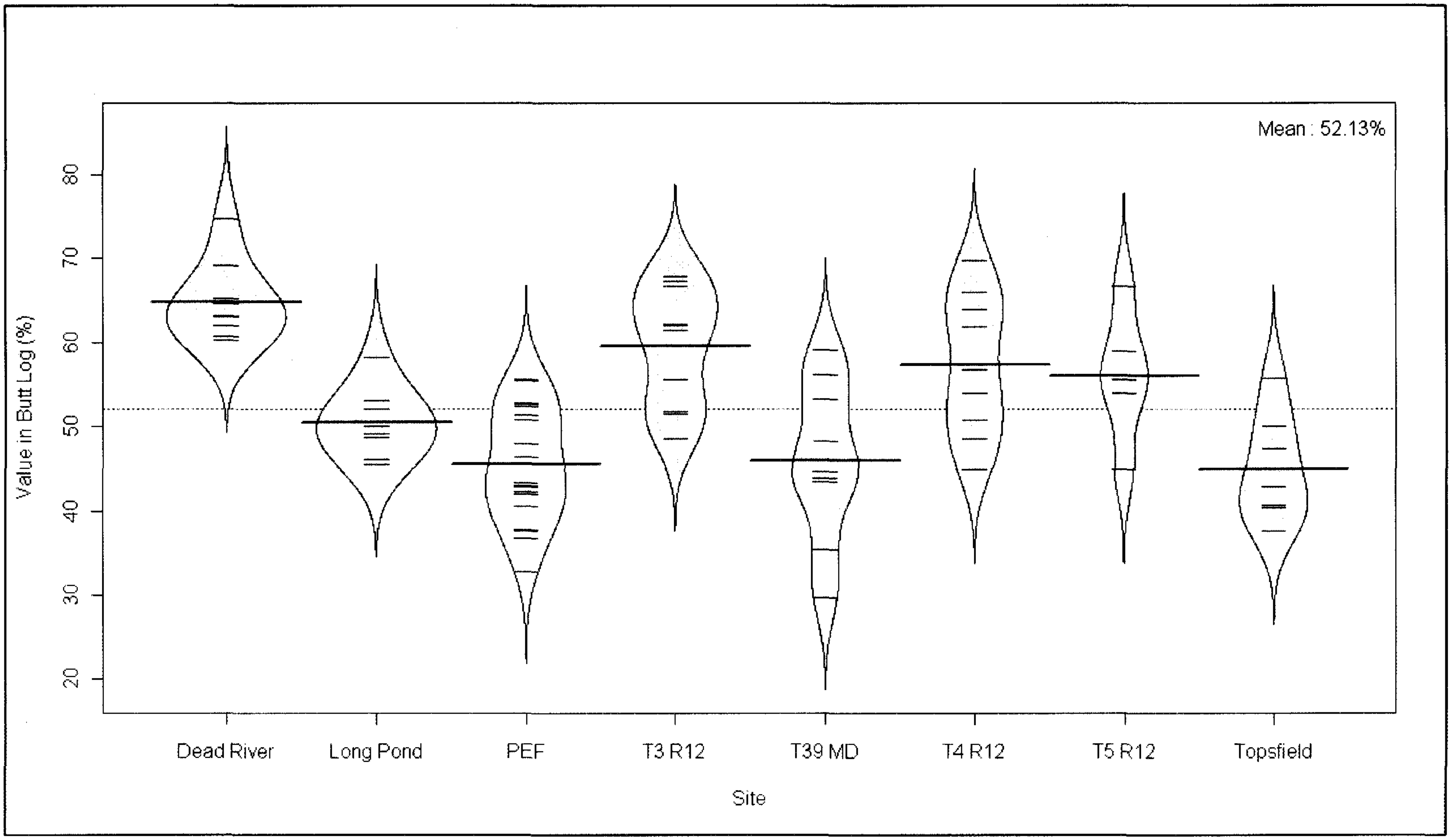

Figure 2.12. Beanplot of the percent of tree value found in the butt log. Small horizontal lines represent individual observations, and large horizontal lines represent site means. Dashed line across entire figure represents grand mean (52.13).

CONCLUSIONS

In addition to providing silvicultural, ecological, and aesthetic benefits, retaining mature eastern white pine trees as reserves through a second rotation appears to be financially viable, as long as careful consideration is given to the selection of vigorous trees. While pruned trees will generally be financially mature at the time of release, the net benefit of pruning will persist, and undiscounted values will increase over the course of the following softwood rotation. The retention of eastern white pine as reserves is especially advantageous on productive sites, where growth rates will increase values at a substantially higher rate than discount rates. Future work in this area should include destructive sampling and detailed stem analysis, to assess the true influence of a two-aged silvicultural system on the knotty core diameter of eastern white pine trees. This would also allow for a more accurate assessment of lumber recovery and valuation of top logs, especially below the crown base, as some knot-free lumber would likely be recovered from that portion of these trees.

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