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Red pine (*Pinus resinosa* Ait) plantations are an important cover type of Department of Natural Resources (DNR) lands because of relatively high yields and economic value. Out of the approximate 400,000 acres of Minnesota red pine plantations one-fifth of the acreage is managed by the DNR. The DNR recently established a policy to rescind purposeful management to manage all red pine plantations to extended rotation ages, or rotation ages beyond those maximizing economic returns or biological yields. With recent state budget issues, DNR management is under greater scrutiny by the public, particularly on School Trust lands. Hence, most red pine plantations are now going to be managed on economic rotation ages (both School Trust and Non-trust lands). The objective of this study was to use a growth and yield model system to help determine the optimal number of thinnings, residual stand density following thinnings, and final harvest rotation age to maximize economic returns. Stumpage revenues received by the DNR from fiscal years 2011 to 2014 were used, allowing for a sensitivity analysis of the optimum thinning scenario since four distinct sets of stumpage revenues were compared. For simplicity, it was assumed that all harvested timber was red pine. Five different thinning treatments and an unthinned scenario were examined. Thinning scenarios differed as to the timing of thinnings based on standing basal area per acre and the residual basal area per acre following the thinning. A final harvest was implemented, the timing differing among the scenarios based on when financial returns were maximized. The greatest economic return appears to occur when light, but frequent thinnings occur. A target basal area of 150 square feet leaving 120 square feet was optimum (150_120) for all four sets of revenues. Optimum final harvest rotation ages varied from 60 to 70 years depending on the stumpage revenues. A thinning scenario of a target 150 square feet leaving 90 square feet (150_90) was nearly financially optimum and would likely allow for more operationally realistic thinning regimes. VanderSchaaf CL, Holley G, Arends A, Adams J, Deckard D. Comparing Economic Returns of Red Pine Plantation Thinning Scenarios Using Forest Vegetation Simulator (FVS). *Minnesota Academy of Science Journal*. 2016; **80:**1-11.
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Abbreviations: DNR – Department of Natural Resources, MAI – mean annual increment, USDA – United States Department of Agriculture, FIA – Forest Inventory and Analysis, FVS – Forest Vegetation Simulator, LS – Lake States, DBH – diameter at breast height, DIB – diameter inside-bark, MMB – Minnesota Management and Budget, SEV – soil expectation value, BA – basal area per acre, SDI – stand density index, BLV – bare land value, Dq – quadratic mean diameter, MFI – Minnesota Forest Industries, FIM – Forest Inventory Module.

INTRODUCTION

Although red pine (*Pinus resinosa* Ait) plantations exist on a relatively low acreage compared to other cover/forest types such as aspen (*Populus* spp.) and black spruce (*Picea mariana* (Miller) B.S.P.), it is an important cover type of Minnesota Department of Natural Resources (DNR) lands. This cover type has relatively high yields, large economic value[1], and importance to several individual mills[2]. Red pine is sold as pulpwood and utilized by several engineered-wood and paper mills within Minnesota (such as Boise Incorporated in International Falls and Verso Paper in Duluth), but it is most highly desired by sawmills such as Potlatch Corporation in Bemidji, Rajala Timber Company in Deer River, and Hedstrom Lumber Company in Grand Marais.

It is believed by many resource managers that older forests are existing on the landscape without requiring purposeful management to maintain them in that older state because of the recent reductions in statewide harvest levels relative to levels in the mid-90's and early 2000's[2]. This belief in large part led to the DNR recently establishing a policy to rescind a formerly established policy mandating purposeful management to manage all red pine plantations to extended rotation ages (or ages past maximum economic return or biological rotation ages calculated using Mean Annual Increment [MAI]). Plantations were formerly managed to be clearcut at extended rotation ages of 100 years or greater, the minimum extended rotation age differed slightly across the state depending on ecological conditions. Given recent state budget issues the public is more critical of DNR forest management and the financial returns generated by DNR forests, particularly on School Trust lands. Hence, because of less concern about the amount of older forest on the landscape and concern about financial returns, most red pine plantations are now being managed on shorter, economic rotation ages (both School Trust and Non-Trust lands). It should be clarified that stands designated to be managed as extended rotations differ from an old growth designation because extended rotations still include a final harvest whereas old growth stands do not generally include a final harvest.

According to the DNR's Forest Inventory Module (02/17/2012), there is a total of 7,583 red pine stands. Figure 1 shows the distribution of stands classified as red pine (111,561 acres, Stand Origins of 0, 1, 2, and 3). Origin is a term used by the DNR representing how a stand was established. A Stand Origin of 2 is classified as red pine plantation (5,045 stands, 81,210 acres, Stand Origin of 2). Stand Origins of 0, 1, and 3 are classified as lacking evidence of enough artificial regeneration to be considered plantations (2,538 stands, 30,351 acres). Most plantations are in mid-rotation age classes of 25 to 45 years (Figure 2).

Figure 3 presents estimates of number of acres by age-class across all ownerships using USDA Forest Service Forest Inventory and Analysis (FIA) data[2]. The greatest percentage of red pine plantation acreage is owned by private landowners (including "industrial" landowners such as Potlatch Corp.). The DNR possesses around one-fifth of the red pine plantation acreage.

Optimum silvicultural systems will likely vary depending on management objectives. At a broad scale, management objectives may, for example, be to maximize economic returns, to maximize volume production, or could be to even maximize volume production of a particular product class. Most likely, to meet one of these three objectives, the optimum stand densities across time will differ.

Several assessments of optimum red pine thinning regimes have been conducted. Ek, *et al*.[3] recommend thinning pole size stands (5 to 9 inches diameter) at a target basal area per acre of 140 square feet back to 90 to110 square feet per acre. Penner, *et al*.[4] found that lower residual densities increased average tree diameter for red pine plantations in southeastern Ontario – consistent with many other studies[5-7]. Penner, *et al*.[4] concluded that outside of extreme residual densities, thinning had little impact on total cumulative (standing plus thinned) cubic foot volume production. Using data from a plantation in southeastern Ontario, von Althen, *et al*.[8] found basically no difference in 5-year merchantable volume increment production during four thinnings conducted nearly every 10 years, the residual thinned basal area was near 140 square feet while the unthinned residual basal areas ranged from 201 to 224 square feet.

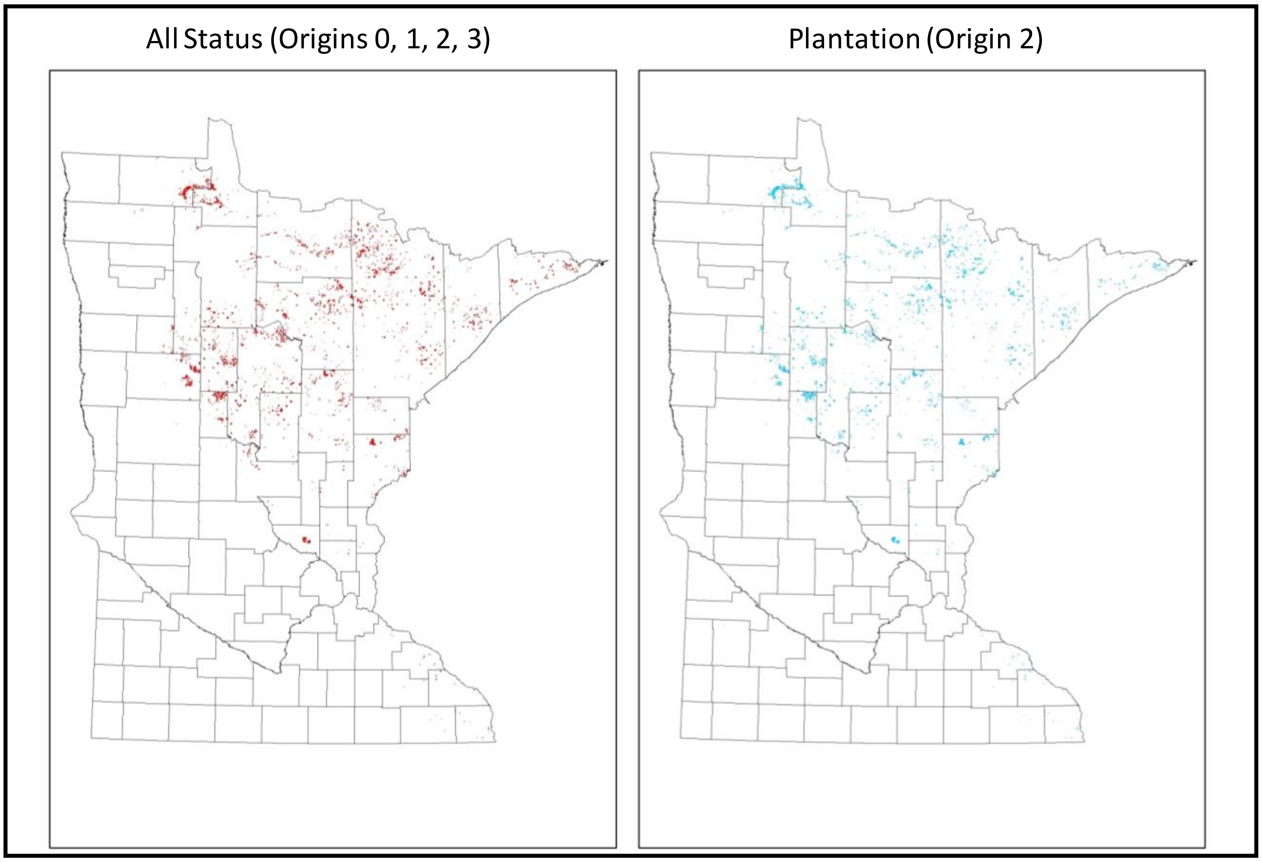

Figure 1. Spatial distribution of stands designated as red pine cover type within the Minnesota Department of Natural Resources Forest Inventory Module (FIM) - stand Origins of 0, 1, 2, and 3. There are 7,583 stands totaling 111,561 acres. Red pine plantations exist on 5,045 stands and 81,210 acres (Stand Origin of 2). Origin refers to method of regeneration.

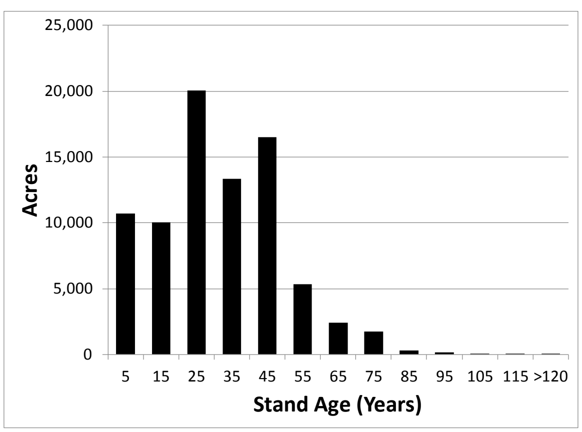

Figure 2. Existing harvestable (excludes old growth designated stands and other stands designated as non-harvestable) red pine plantation cover type (Stand Origin of 2) age-class distribution (FIM 03/08/2012). Total number of stands is 4,792 and the total number of acres is 80,726. An age-class of 35 corresponds to stands aged 31 to 40 years.

Gilmore, *et al.*[9] found that 10-year volume production was maximized at a residual density of 140 square feet (as compared to 100, 120, and 180 square feet) – but this study was extremely limited in terms of sample size and the residual basal areas resulted from different thinning methods (strip, low, and crown), however, observations are actual field observed data in Grand Rapids, Minnesota. Coffman[6], in western Upper Peninsula Michigan plantations, concluded that residual basal areas from 90 to 140 had very little impact on total cumulative volume production 3 years after thinning a 18 year old high site quality (site index 81 feet – base age 50) plantation – however, row thinning during the first thinning may reduce volume increment as opposed to "free" thinning. Although row thinning is often operationally advantageous, a decrease in volume may be observed as row thinning removes both inferior and superior trees. Cooley[5], from observations of 19 and 22 year old plantations in Lower Michigan, found that residual basal areas from 60 to 150 when thinning from below had very little impact on periodic basal area growth. However, basal area is not necessarily always consistent with merchantable volume.

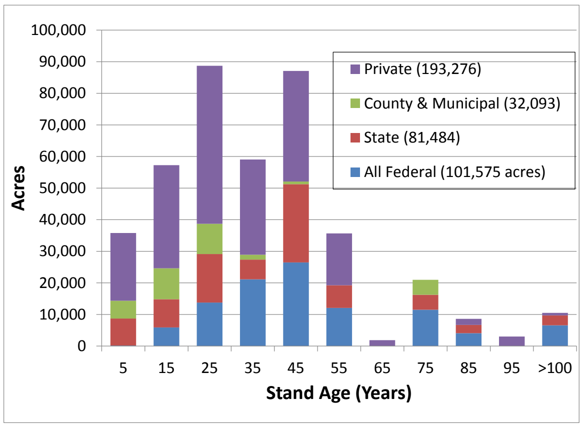

Figure 3. Amount of timberland acres on the MnDNR Red Pine Plantation forest type (excludes SITECLCD = 7 which is forestland and RESERVCD = 1) within Minnesota by ownership according to the 2014 USDA Forest Service Forest Inventory and Analysis (FIA) database. Total acreage is 408,428. An age-class of 35 corresponds to stands aged 31 to 40 years.

Lundgren[7], based largely on outputs from a growth and yield model entitled REDPINE developed using data from the Lake States, found that residual basal areas of around 120 to 140 produced the greatest mean annual merchantable cubic-foot volume increment. Grossman and Potter-Witter[10], on site indexes from 60 to 75 feet (base age 50), basically recommended thinning back to 110 square feet or greater to maximize pole production and hence economic returns. They also found that thinnings resulting in 90 square feet or less residual basal area reduced economic returns under the assumption of an existing pole market.

The objectives of this study were to use a growth and yield model system to help determine the optimal number of thinnings, the residual stand density following thinnings, and the final harvest age to maximize economic returns of red pine plantations in northern Minnesota.

MATERIALS AND METHODS

The USDA Forest Service Forest Vegetation Simulator (FVS) growth and yield projection system was used to model stand development in relation to various residual stand densities[11]. FVS is the Forest Service's nationally supported framework for forest growth and yield modeling. It is an individual tree, distance independent growth and yield model. FVS can simulate a wide variety of forest types, stand structures, and pure or mixed species stands.

The Lake States (LS) variant of FVS covers forest areas in the Great Lake states of Michigan, Minnesota, and Wisconsin. This includes Chippewa and Superior National Forests in Minnesota. Chequamegon and Nicolet National Forests in Wisconsin are also included as well as the Hiawatha, Ottawa, Huron and Manistee National Forests in Michigan.

Within FVS, the Bareground option was used to generate a plantation of 600 seedlings per acre with a site index of 65 feet (base age 50). A site index of 65 was selected since it is roughly an acreage-weighted average site index. Survival at age 10 was assumed to be 100%. Discounted regeneration costs were assumed to be \$575 per acre, these costs include \$150 per acre for site preparation, \$225 per acre for seedlings and planting (corresponds roughly to 600 seedlings per acre), \$80 per acre for a release treatment in year 1, and \$40 per acre to conduct bud capping to reduce deer browsing in years 1, 2, and 3. Bud capping involves placing a piece of paper on the terminal bud to reduce the potential that it be eaten by deer during the fall and winter months.

Minimum merchantability limits were consistent with standard FVS protocol. Stump height was 1 foot, minimum merchantable pulpwood DBH was 5.0

inches, and upper stem DIB was 4.0 inches. In addition, bolt and pulpwood (a classification in Minnesota where it is assumed the same tree contains both bolt and pulpwood volume) volume was specified as minimum DBH of 8.0 inches with a maximum DBH of 11 inches, upper stem DIB was 4 inches. Sawlog volume was defined as trees with a minimum DBH of 12 inches and greater to a 7.6 inch top DIB. Pulpwood volume was specified as all merchantable volume obtained from trees with diameters smaller than 8.0 inches and all volume on sawlog sized trees from the 7.6 inch top to the 4.0 inch top.

Stumpage prices were assumed to be $8.83, $28.73, and $49.20 per cord, respectively, for pulpwood, bolt and pulpwood, and sawlog sized trees[12] – average red pine stumpage prices received by the DNR for the 2012 fiscal year (Table 1). Appraisal/marking costs of $14 and $6 per cord were assumed during thinnings and clearcuts, respectively. A 3% interest rate (based on Minnesota Management and Budget [MMB]) was used to produce Soil Expectation Value (SEV). The default FVS max BA (basal area per acre) and SDI was used for red pine plantations, 240 square feet per acre.

At least 10 years had to pass in the simulation following a thinning before a final harvest could be conducted. To account for the opportunity costs associated with varying rotation ages, economic projections are based on SEV, often referred to as Bare Land Values (BLV).

A total of five thinning treatments and a sixth treatment where no thinning was conducted were examined (Table 2). All thinnings were assumed to be from below, or the removal of trees from the lower crown classes to favor those in the upper crown classes. Within FVS, when a stand reached the target BA it was thinned in that year.

Mehne and Burk[13] examined FVS's ability to predict growth and yield of unthinned red pine plantations located on the University of Minnesota's Cloquet Forestry Center near Cloquet, Minnesota. Plantations were established in 1982 and measurements were taken in 2004 and 2011. For planting densities and spacings similar to the one used in this study (600 seedlings per acre), they found FVS produced reasonable estimates.

Table 1. Weighted average stumpage prices from fiscal years of 2011, 2012, 2013, and 2014. The weight is the amount of volume harvested annually by product class. Columns (a) and (b) are multiplied to produce the Weight column. The total weight from all four years is then divided by the total amount of harvested volume across all four years.

	Sawtimber			Bolt and Pulpwood			Pulpwood		
	(a)	(b)	(a)*(b)	(a)	(b)	(a)*(b)	(a)	(b)	(a)*(b)
	Cords	Price	Weight	Cords	Price	Weight	Cords	Price	Weight
2011	3,347	$48.58	162,590	71,765	$33.28	2,388,323	4,510	$23.03	103,875
2012	6,225	$49.20	306,239	40,986	$28.73	1,177,528	4,263	$8.83	37,639
2013	1,496	$55.33	82,785	52,881	$41.54	2,196,668	3,080	$13.50	41,583
2014	1,238	$95.39	118,131	55,101	$47.68	2,627,235	2,473	$5.96	14,740
Total	12,307		669,745	220,733		8,389,754	14,326		197,836
Weighted			$54.42			$38.01			$13.81

Table 2. Description of the five thinning treatments and the unthinned treatment. All thinnings were assumed to be from below. BA is basal area per acre.

Treatment	Description	Representation
1	Unthinned	Unthinned
2	Once stand BA reaches 120 square feet per acre thin back to 60 square feet.	120_60
3	Once stand BA reaches 120 square feet per acre thin back to 90 square feet (probably most common operationally).	120_90
4	Once stand BA reaches 150 square feet per acre thin back to 120 square feet.	150_120
5	Once stand BA reaches 150 square feet per acre thin back to 90 square feet.	150_90
6	Once stand BA reaches 120 square feet per acre thin back to 90 square feet for first thinning, then once stand BA reaches 150 square feet per acre thin back to 120 square feet. This treatment was added after initial runs of the other thinnings, to see if this particular combination would be economically beneficial.	120_90_150_120

RESULTS AND DISCUSSION

As expected, the greatest standing merchantable volume occurs in the Unthinned treatment (Figure 4). For the most part, the thinning treatments show logical progressions throughout time.

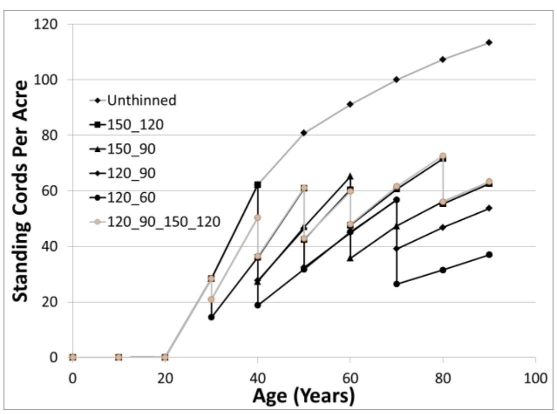

Figure 4. Merchantable cords per acre by thinning treatment. Merchantability is defined as all volume above a 1 foot stump to a 4-inch top DIB on all trees with DBH's of 5 inches or greater.

Figure 5 shows cumulative volumes (total of harvested and standing). Based on assumptions used during this analysis (e.g. regeneration methods, merchantability standards), and growth and yield projections from FVS, thinning increases merchantable stand volume production over time. These results suggest carrying relatively high densities followed by light, frequent thinnings (e.g. 150_120 treatment) will produce the most merchantable volume. Results show the 120_60 thinning treatment does not result in enough utilization of the site – of course this thinning treatment does produce relatively larger standing trees over time (Figure 6).

By age 40, the vast majority of trees in the 120_60 treatment are bolt size – which demand a relatively greater stumpage value than pulpwood. However, all treatments do have some bolt material. In terms of simulated quadratic mean diameter (Dq), results do not show substantial differences among thinning treatments – but thinning vastly increases average tree diameter throughout time. Interestingly, according to the Michigan DNR[14], given current markets, red pine stumpage demands the highest revenues when DBH ranges from 14 to 18 inches, and loses value when 20 inches or larger – hence in some ways the 120_60 and 120_90 treatments may produce trees too large at later ages such as 90 and 100 years.

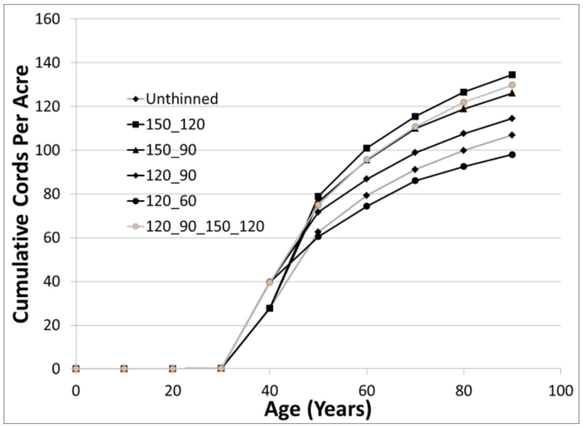

Figure 5. Cumulative merchantable cords by thinning treatment. Merchantability is defined as all volume above a 1 foot stump to a 4-inch top DIB on all trees with DBH's of 5 inches or greater.

Despite the high intensity thinning (120_60) to produce larger trees, the site was not utilized to its capacity and given current markets, produced the least optimum economic return (Figure 7). It should be noted that economic analyses in this report do not account for potential stumpage revenue decreases as trees become relatively large (e.g. 20 inches DBH and larger) – if this was accounted for, the economics may look even worse for the 120_60 treatment. Besides the 120_60 thinning regime, all other thinning regimes produced economic benefits relative to only conducting a final harvest, or not thinning at all.

Optimum rotation ages varied from 60 to 80. The Unthinned and high intensity thinning (120_60) treatments, and actually a common operational scenario (120_90) thinning treatment, produced only negative returns. Given current markets, growth rates of the Unthinned stand were not large enough to offset opportunity costs and hence a young optimum rotation occurs. For the 120_60 treatment, it appears that holding the trees for a longer time better captures this thinning's ability to produce larger, more valuable trees. Perhaps if a real price increase on sawtimber is included (up to around 20 inches in diameter), this treatment may become better.

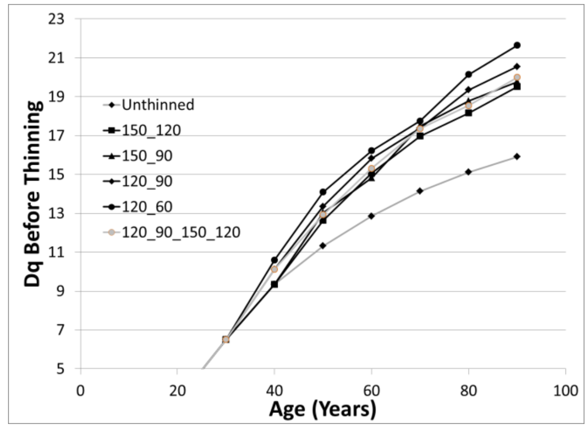

Figure 6. Quadratic mean diameter (Dq - inches) by thinning treatment – before thinning.

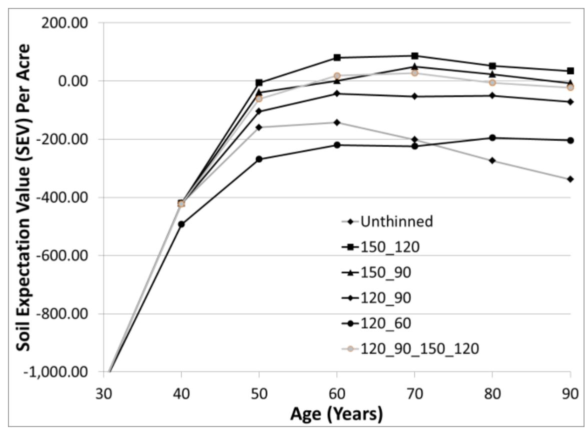

Figure 7. Soil Expectation Value (SEV/BLV) by thinning treatment. Merchantability is defined as all volume above a 1 foot stump to a 4-inch top DIB on all trees with DBH's of 5 inches or greater. Stumpage values (2012 prices) are $8.83, $28.73, and $49.20 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively. A 3% interest rate was assumed.

When using 2012 stumpage revenues, the greatest economic return appears to occur when light, but frequent thinnings occur (150_120). To show the sensitivity of the optimal harvest regime to assumed stumpage values, prices from the 2011 fiscal year received by the DNR for red pine were used[15], $23.03, $33.28, and $48.58 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively. Additionally, prices from the 2014 fiscal year received by the DNR for red pine were used[1], $5.96, $47.68, and $95.39 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively. These three sets of revenues are actual data but do show the variability from year to year. This is particularly true for the pulpwood and sawlog product classes for red pine which have relatively less volume harvested each year and hence have more variability than the bolt and pulpwood class.

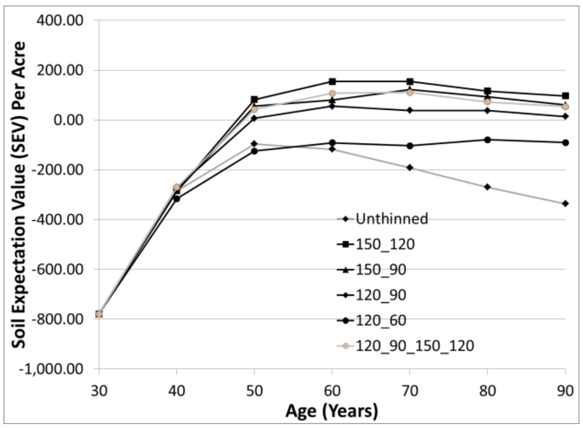

Figure 8. Soil Expectation Value (SEV/BLV) by thinning treatment. Merchantability is defined as all volume above a 1 foot stump to a 4-inch top DIB on all trees with DBH's of 5 inches or greater. Stumpage values (2011 prices) are $23.03, $33.28, and $48.58 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively. A 3% interest rate was assumed.

Variability in revenues arise not only because of changes in annual market conditions due to demand factors such as housing starts, the economy, etc., but also annual differences across the state in the particular characteristics of what stand types are actually harvested and localized markets since these prices are statewide averages. For instance, the ratio in acreage between the amount of thinned acres and final harvested acres due to forest management constraints (e.g. even-flow constraints of statewide harvested volumes) will likely impact the amount of pulpwood harvested annually. Thus, one final set of revenues for each product class was examined (Table 1). These were weighted average prices by harvest amount from each year using reported revenues from years 2011 to 2014 (inflation was ignored). Weighted revenues were (where 2013 revenues[16]), $13.81, $38.01, and $54.42 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively.

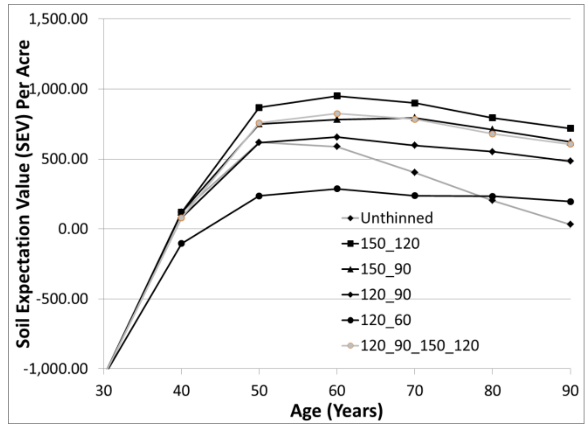

Figure 9. Soil Expectation Value (SEV/BLV) by thinning treatment. Merchantability is defined as all volume above a 1 foot stump to a 4-inch top DIB on all trees with DBH's of 5 inches or greater. Stumpage values (2014 prices) are $5.96, $47.68, and $95.39 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively. A 3% interest rate was assumed.

Despite a substantial difference in pulpwood stumpage revenues from 2011 to 2012, in terms of the optimal treatment, little difference was seen when using 2011 stumpage values (Figure 8). Given 2011 revenues, the 120_90 optimum economic return became positive while the Unthinned rotation age was reduced from 60 to 50 years. Most likely this is because of the substantial increase in pulpwood revenues – for the 120_90 treatment this likely results from the assumption that on all sawlog trees (12 inches and greater), all non-sawlog volume is assumed to be pulpwood. For 2011 prices, the best economic return (from the 150_120 treatment) appears to occur at either age 60 ($154.00 SEV) or at age 70 ($154.15 SEV), shorter rotation ages are often advantageous because they can reduce risk associated with timber damage and fluctuations in the market – additionally the small difference in optimum economic returns allows landowners some flexibility as to the timing of final harvest, allowing flexibility particularly in relation to current markets. Using 2014 fiscal year revenues (Figure 9), despite low pulpwood revenues, all scenarios produced positive economic returns. Obviously the highly advantageous sawtimber revenues help to produce this result. However, based on the other three fiscal years, this stumpage revenue is not consistently received (Table 1). Once again the greatest economic return appears to occur when light, but frequent thinnings occur (150_120). However, using 2014 revenues show a more distinct optimum occurring at age 60 for this thinning scenario.

Similar to the three annual revenues, the weighted revenues also show that the greatest economic return appears to occur when light, but frequent thinnings occur (150_120) with the optimal rotation age being around 60 to 70 years (Figure 10). The (150_90) scenario once again appears to be relatively competitive with an optimal rotation age of around 70. Once again the (150_120) scenario may be difficult to implement operationally and hence the (150_90) scenario may be the best alternative.

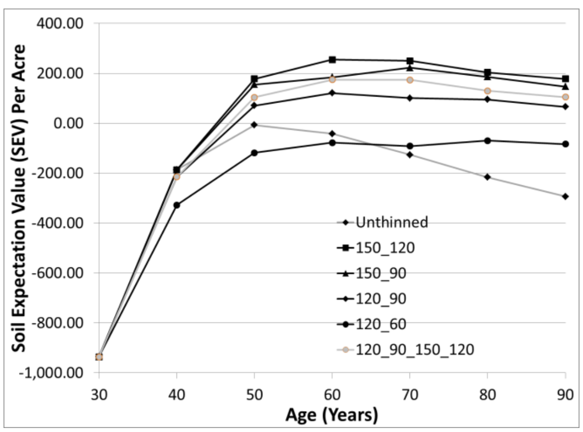

Figure 10. Soil Expectation Value (SEV/BLV) by thinning treatment. Merchantability is defined as all volume above a 1 foot stump to a 4-inch top DIB on all trees with DBH's of 5 inches or greater. Stumpage values (weighted average) are $13.81, $38.01, and $54.42 per cord for pulpwood, bolt and pulpwood, and sawtimber, respectively. A 3% interest rate was assumed.

Thinnings first occurred at age 30 for the 120_60, 120_90, and 120_90_150_120 regimes, at age 40 for the 150_90 and 150_120 regimes (Figure 4) – remember projections were on a 10-year interval, first thinnings may have occurred at ages of 25 or 35 if run on a five-year interval.

As expected, the number of thinnings differed by treatment. Three thinnings occurred for the 120_60 regime (ages 30, 40, and 70), four thinnings occurred for the 120_90 regime (ages 30, 40, 50, and 70), two thinnings occurred for the 150_90 regime (ages 40 and 60 – of course with greater volumes per thinning), four thinnings occurred for the 150_120 regime (ages 40, 50, 60, and 80), while five thinnings occurred for the 120_90_150_120 regime (ages 30, 40, 50, 60, and 80). Within many recent DNR landscape modeling efforts, for red pine plantations of site index 45 and greater (base age 50), up to six thinnings can occur where each generates 10 cords per acre. Currently, Minnesota Forest Industries (MFI), assumes three thinnings will occur where the first generates 10 cords (must occur between ages 30 and 40), the second 12 cords (must occur between ages 45 and 50), and the third 15 cords per acre (must occur between ages 55 and 60).

For the 120_60 regime, thinning cords ranged from 14 to 30 averaging 21 cords per acre, the 120_90 regime, thinning cords ranged from 7 to 23 averaging 16 cords per acre, the 150_90 regime, thinning cords ranged from 29 to 35 averaging 32 cords per acre, while for the 150_120 regime, thinning cords ranged from 13 to 26 averaging 18 cords per acre, while for the 120_90_150_90 regime, thinning cords ranged from 7 to 18 averaging 14 cords per acre.

Langsaeter's Hypothesis

According to Gilmore, *et al.*[9], Langsaeter stated:

"The total production *(refers to both standing and cut)* of cubic volume by a stand of given age and composition on a given site is, for all practical purposes, constant and optimum for a wide range of density of stocking. It can be decreased, but not increased, by altering the amount of growing stock to levels outside this range."

However, Gilmore, *et al.*[9] question the validity of Langsaeter's hypothesis. They found that 10-year volume production was maximized at a residual density of 140 square feet (as compared to 100, 120, and 180 square feet) – but their study was extremely limited in terms of sample size and the residual basal areas resulted from different thinning methods (strip, low, and crown). Ek, *et al.*[3] recommend thinning pole size stands (5 to 9 inches diameter) at a target basal area per acre of 140 square feet back to 90 to110 square feet per acre. Lundgren[7], based on a growth and yield model entitled REDPINE developed using data from the Lake States, found that residual basal areas of around 120 to 140 square feet produced the greatest mean annual merchantable cubic-foot volume increment.

However, consistent with Langsaeter's hypothesis, Coffman[6], in western Upper Peninsula Michigan plantations, concluded that residual basal areas from 90 to 140 square feet had very little impact on total cumulative volume production 3 years after thinning a 18 year old high site quality (site index 81 feet [base age 50]) plantation – however, row thinning during the first thinning may reduce volume increment as opposed to "free" thinning. Penner, *et al.*[4] concluded that outside of extreme residual densities, thinning had little impact on total cumulative (standing plus thinned) cubic foot volume production. However, this study using FVS shows that residual densities can have a substantial impact on cumulative merchantable volume (Figure 5). Cooley[5], from observations of 19 and 22 year old plantations in Lower Michigan, found that residual basal areas from 60 to 150 square feet when thinning from below had very little impact on periodic basal area growth – this would be similar to Langsaeter's hypothesis (except Langsaeter referred to volume). However, basal area is not necessarily always consistent with merchantable volume.

Somewhat consistent with Ek, *et al.*[3], and contrary to Langsaeter's hypothesis, this study using FVS basically recommends thinning at 150 square feet back to 120 square feet – both in terms of total merchantable volume production as well as economic returns. However, thinning back to 90 square feet at the 150 square feet target produced little difference from the optimum 120 square feet. If thinning back to 120 square feet is not operationally feasible, then, consistent with previous management, thinning back to around 90 or 100 square feet appears to be optimum. This study also shows that a manager has some flexibility as to target tree size – residual densities from 90 to 120 square feet will produce different sized-trees (with essentially no loss in volume), and will likely produce trees of different product classes if local markets allow.

Management Recommendations

The greatest economic return appears to be when light, but frequent thinnings occur (150_120) with the optimal rotation age being around 60 to 70 years. The 150_90 scenario is relatively competitive with an optimal rotation age of around 70. Operationally, due to the time and costs associated with thinnings, the 150_90 scenario may be more practical to implement.

Two thinnings occurred for the 150_90 regime (ages 40 and 60 – of course with greater volumes per thinning), four thinnings occurred for the 150_120 regime (ages 40, 50, 60, and 80), and five thinnings occurred for the 120_90_150_120 regime (ages 30, 40, 50, 60, and 80). Remember projections were on a 10-year interval, first thinnings may have occurred at ages of 25 or 35 if run on a five-year interval. Although the 120_90_150_120 scenario generally had lower financial returns than the 150_90 scenario, it does allow for an earlier first thinning, and for some sets of revenues this scenario produced greater financial returns than the 150_90 scenario. Managers may not want to wait until age 35 or 40 to conduct a first thinning and hence this alternative is a viable option. Earlier thinnings help to reduce financial risk since revenues are received sooner in the rotation. Although yields and the stumpage revenues (e.g. earlier thinnings will likely have a greater percentage of their volume in the less valuable pulpwood class and lower amounts of volume in the more valuable bolt product class) may be less as the age of the first thinning is reduced, the impacts of the interest rate (or time value of money) on financial returns is less.

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